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Integrated Iron and Nitrogen Control for Lake Restoration

Carr Research Lab., Inc.
Wellesley, MA

Prepared for

Environmental Protection Agency
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Nov 79

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The project is unique in that nitrogen is the focus of the lake management program; whereas phosphorus is the focus in all the other Clean Lake Programs. In addition, this program is unique in that it deals with the impact of the micro-nutrient iron in the aquatic environment. By controlling iron, nuisance blue-green algal blooms may be brought under control. Morses Pond in Wellesley, Massachusetts was given three different treatments to remove the iron and control the algae.

KEYWORDS: *Algae, *Morses Pond, *Water pollution control, *Eutrophication.

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INTEGRATED IRON AND NITROGEN CONTROL FOR LAKE RESTORATION

NOVEMBER, 1979

U.S. ENVIRONMENTAL PROTECTION AGENCY
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INTEGRATED IRON AND NITROGEN CONTROL FOR LAKE RESTORATION

by

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November, 1979

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FOREWARD

Lakes and reservoirs are a critical part of man's environment. They serve as water supplies and major recreational areas. These valuable resources must be protected from pollution, and where already degraded via eutrophication, must be managed or reclaimed. The Clean Lakes Program 314 (a) of the EPA contributes to the protection, management and reclamation by increasing knowledge of lakes via Research and Demonstration Programs.

This report documents one of the more unique projects in the Clean Lakes Program. The project is unique in that nitrogen is the focus of the lake management program; whereas phosphorus is the focus in all the other Clean Lake Programs. In addition, this program is unique in that it deals with the impact of the micro-nutrient iron in the aquatic environment. By controlling iron, nuisance blue-green algal blooms may be brought under control. → Morses Pond in Wellesley, Massachusetts was given three different treatments to remove the iron and control the algae. ←

ABSTRACT

This research and demonstration project involves a complex program aimed at actual restoration of Morses Pond in Wellesley, Massachusetts as well as advancing the state-of-the-art of lake management. There are many new concepts that were developed during the course of this total program. Foremost among these concepts are:

1. that nitrogen limited lakes can be managed by nitrogen control; and
2. that the nitrogen fixing algae, which may contribute a major portion of a lake's nitrogen budget via nitrogen-fixation, can be controlled by stripping iron from the lake.

The chemical used in Morses Pond since 1975 for this iron stripping was potassium permanganate ($KMnO_4$). This chemical not only removed the iron from the algal community but also reduced color in the water and destroyed the organic complexes in the water that stimulate total algal growth. Thus the treatment program not only altered the algal community from blue-green algal dominance to green algal dominance, but lowered total phytoplankton biomass.

Other contributions of this research and demonstration program include development of a better understanding of

- nutrient budget analysis relative to the Vollenweider curves;
- the chemistry of base flows and storm flows;
- the role of cations relative to algal bloom potential;
- phytoplankton and visibility relationships;
- biological community response to dredging; and
- the actual management of a major dredging program.

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LIST OF ABBREVIATIONS AND SYMBOLS

alum = aluminum sulfate
ASU/ml = areal standard units per milliliter
Ca = calcium
$CuSO_4$ = copper sulfate
DO = dissolved oxygen
Eh = redox potential = oxidation-reduction potential
ha = hectares = 10,000 square meters
ha-m = hectare meters = 10,000 cubic meters
K = potassium
kg = kilograms
km = kilometers
$KMnO_4$ = potassium permanganate
m = meters
Mg = magnesium
mg/l = milligrams per liter = ppm
MnO_2 = manganese dioxide
Na = sodium
pH = hydrogen ion activity
ppm = parts per million = mg/l
USGS = U.S. Geological Survey

KEY WORDS

For reference purposes, the key words for classification of this report are:

algae, algal blooms, alum, *Anabaena*, *Aphanizomenon*, biological substitution, cations, dredging, eutrophication, iron, iron metabolism, lake management, limnology, limiting nutrient, micro-nutrients, nitrogen fixation, non-point sources, nutrient inactivation, potassium permanganate, phytoplankton, urban runoff, *Volvox*, water pollution control.

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This report describes and documents the technical aspects of the Morses Pond Research and Demonstration Program funded jointly by the U.S. Environmental Protection Agency, the Massachusetts Division of Water Pollution Control through its director Thomas C. McMahon, and the Wellesley Department of Public Works. This lake restoration program would not have been possible without the cooperation of the Board of Public Works, Town of Wellesley, Massachusetts who had the courage to accept the risk in trying a proposed new lake management technology. Such courage is rare at any level of bureaucracy.

This program was more than a research project. It included considerable work and effort involving daily maintenance of a lake undergoing active recreational use, as well as long term lake restoration efforts including dredging. Thus, special recognition is required for all the staff of the Wellesley Department of Public Works who participated in the program; especially John Bezanson, James Campbell, Grace Cresine, Richard Davitt, Ronald Despres, and Fred Dodge who have all had major responsibilities on the project since 1975.

Thanks are also due to Wellesley College who allowed the town the use of its land for a dredging spoils confinement area. In addition, we wish to acknowledge the work by John J. Paonessa Company and Northeast Dredging Company in carrying out a dredging job with all the constraints imposed by working in an almost completely developed community.

1.0 EXECUTIVE SUMMARY

Morses Pond in Wellesley, Massachusetts is a man-made lake with and area of 41.5 ha (102 acres) and is connected to a small fish pond of 1.9 ha (5 acres). The lake has a mean depth of 2.4 m (7.7 feet). This lake has suffered from intensive blue-green algal blooms from the mid 1960's and it became impossible to control these blooms with copper sulfate ($CuSO_4$) alone in 1973. Visibility in 1973 and 1974 was less than the 1.25 m (4 feet) required by Massachusetts law for public recreational swimming. Thus the beach was closed for portions of these years. During that time the town considered the construction of a two million dollar swimming pool complex as a suppliment to the town swimming program and as a possible replacement to Morses Pond should it remain unsuitable for contact recreation. One of the reasons why the pool complex was not built was that in 1975 the new lake management technique described herein, restored visibility on the lake to well over 3 meters (11 feet plus).

The technique used in 1975 involved:

- immediate treatment of blue-green algae with $CuSO_4$ as soon as they reached pre-bloom levels in the lake;
- use of potassium permanganate ($KMnO_4$)to remove iron from the system; and
- use of alum to remove the residual manganese dioxide (MnO_2) left by the $KMnO_4$ treatment.

Based on the experience over 5 years, two things are known. First, the reduction of biomass was not due to use of alum, because in 1974 alum was used in July without $KMnO_4$, and the biomass reduction did not match the reductions achieved in later years. Second, we know that the $KMnO_4$ did not act as an algicide because there were no significant changes in algal populations on the few days after $KMnO_4$ treatments. Thus the long term biomass reductions and the significant reduction of blue-green algae were due to removal of iron from the lake waters.

Besides the yearly chemical management programs, the town began a long term lake restoration and management program once they knew the lake could be managed. This long term program, combined with a modest research effort, was funded jointly by the Wellesley Department of Public Works (25%), the Massachusetts Division of Water Pollution Control (25%), and the U.S. Environmental Protection Agency (50%) under their 314(a) Clean Lakes Program.

The long term restoration portion of the program involved 8 separate tasks:

1- leaf load reduction;
2- removal of emergent vegetation;
3- control of water lilies and pondweeds;
4- public education;
5- protection of key wetlands above the lake;
6- control of periphyton;
7- chemical maintenance (using $KMnO_4$ and alum); and
8- dredging.

The research portion of the program was aimed at:

1- evaluation of use of $KMnO_4$ in open water; and
2- evaluation of the impacts of dredging.

In order to perform these evaluations it was necessary to implement a monitoring program which would allow development of a water budget and nutrient budget for the lake as well as determine the biological response to the lake to all the reclamation activites.

In the course of this project, issues were encountered that are related to fundamental relationships in lake systems behavior. Where this project has impinged on these larger limnological issues, and where these issues have been at least partially resolved during this project, the resolution of these issues is presented in this report.

Summary

Morton and Lee (1974) demonstrated in laboratory tests that iron in concentrations of 0.1 to 1.0 mg/l causes a shift in algal dominance from green algae to blue-green algae. In this program it has been demonstrated that this dominance can be reversed in the real world by stripping iron from lake waters by use of $KMnO_4$. The application of this principle has two important results. First, there is a new technique to manage lakes subject to undesirable blooms of blue-green algae. This is valuable because it allows recreational lake use while longer term management programs are being implemented. Second, the ability to control nitrogen-fixing blue-green algae means that nitrogen management of nitrogen-limited lakes may, in many cases, be more effective and more cost-effective than trying to control some other nutrient that is not the limiting nutrient.

In addition, this project allowed research on nutrient budget calculation techniques, chemistry of non-point sources, algal response to cations, visibility in lakes relative to phytoplankton biomass, and aquatic plant community response to dredging.

On a more practical level, this project represents one of the first large scale in-lake dredging programs in New England. Thus, a great deal was learned about the total nature and character of dredging as a lake restoration technique.

Conclusions

1- Once seed populations are controlled, stripping of iron from lake water by use of $KMnO_4$ blocks repeated blooms of nitrogen fixing blue-green algae. Anabaena is not as sensitive to reduction of iron as is Aphanizomenon. Anabaena can reach pre-bloom levels in iron stripped lakes. At this early stage, control by $CuSO_4$ is easily achieved. Aphanizomenon is much more sensitive to iron deficiency and has been driven almost to extinction in iron deficient Morses Pond.

2- Timing is critical to all lake management events, especially where control of nitrogen fixation is desired.

3- Potassium permanganate use in open waters is effective via inactivation of the key micro-nutrient iron, and is not due to any algicidal properities of $KMnO_4$.

4- Use of the Vollenweider curves for a nutrient that is not limiting in a specific lake system, can lead to significant errors in the evaluation of a lake's trophic status. This in turn can lead to a poor selection of lake restoration methods.

5- Calculation of a lake's internal nutrient loading is necessary to properly evaluate a lake's nutrient budget. Inclusion of internal nutrient sources in no way invalidates the second set of trophic status curves developed by Vollenweider (1975).

6- Based on water quality monitoring, the chemical equivalent of base flow is 83% of total annual runoff while the chemical values of storm flow apply to only 17% of the average annual runoff. These figures should only be used in eastern New England and should be adjusted for residential and urbanized drainage basins.

7- Storm loading of nitrogen, phosphorus and iron appear to correlate with both storm intensity and with total amount of rainfall . This makes sense because rainfall intensity correlates with total rainfall.

8- The use of Perrsall's cation ratio, which equals (Na + K)÷(Ca + Mg) is not valid as a predictor of algal bloom potential for New England lakes because of the effects of highway salting.

By use of a standard value of 5 for sodium, lakes with cation ratio values less tha 0.5 are subject to algal blooms while lakes with values greater than 0.6 are not subject to algal blooms. Further research may modify this criterion.

9- Phytoplankton cell counts do not correlate with secchi disk visibility due to the extreme range in sizes of algal cells. However, phytoplankton biomass as measured in Areal Standard Units per milliliter (ASU/ml) does correlate well with secchi disk visibility providing the water is not colored or turbid (inorganic particles such as clays in suspension). *Volvox* is a known exception and large *Volvox* counts (>2000 ASU/ml) do not have a significant impact on visibility.

10- Dredging during the late fall (November - December) and early spring (April - May) seemed to result in some minor suppression of phytoplankton productivity. However, during the late spring and summer dredging clearly enhanced phytoplankton growth to the point where maintaining visibility in the lake became difficult. It is quite likely that if dredging activities were not constrained by a limited spoils area, visibility management could have been so expensive that the beach would have been closed to public recreation.

The aquatic macrophyte response to dredging included:

- drifting of white water lily (*Nymphaea odorata* Ait.)and spatterdock (*Nuphar variegatum* Engelm.) rhizomes and arrow arum (*Peltandra virginica* (L.) Kunth.) plants from the dredging area;

- drifting and rerooting of water milfoil (*Myriophyllum heterophyllum* Michx.) into dense concentrations in undredged areas;

- sprouting of seedling of spatterdock and slender arrowhead (*Sagittaria graminea* Michx.), the latter plant not being seen previously in the dredged area; and

- a layer of mixed organic and inorganic mud was deposited in undredged areas nearest the dredging site.

11- Considerable cleanup activities were necessary during and immediately after the dredging, particularly when dredging occurred in concentrations of spatterdock and arrow arum.

12- Dredging costs can be broken into the actual cost of moving sediment and all the associated costs of a total project. These other cost items are an essential part of any dredging operation and include pre- and post dredging surveys, security, design and construction of the spoils area, engineering inspection, and the complex approval process. The accepted bid for actual movement of sediment was $5.01 per cubic meter ($3.83 per cubic yard), using a large commercial dredge. However, when all of the other essential costs were added in, the cost became $11.77 per cubic meter ($9.00 per cubic yard). This still does not include costs for final rehabilitation of the spoils area.

General Lake Management Recommendations

1- In evaluation of a lake restoration program, deal with the limiting nutrient in the system. Do not blindly accept a management program based on phosphorus control when nitrogen is the limiting nutrient.

2- Where nitrogen-fixation is a large portion of a lake's total nitrogen budget, use of $KMnO_4$ should be considered as a part of the total management program.

3- Where dredging is to be considered as an essential part of a lake restoration program, and where the dredging volume to be moved is large, consideration should be given to community purchase of a small dredge. This can be substantially more cost-effective under some circumstances than use of a large commercial dredge.

4- For dredging, if the town is going to perform the engineering function, someone has to be assigned to the project on an almost full time basis.

5- Given the total complexity of a dredging operation including selection of a spoils area, getting all the permits, drawing up the engineering specifications, etc., allow three years as a reasonable duration of even a small dredging program.

6- All dredging programs that are close enough to impact public recreational beaches, should include funds for turbidity or visibility control. Also, where dredging is scheduled in areas with dense water lilies or arrow arum, funds should be allocated for removal of floating debris while the dredge is operating.

7- Any community managing a recreational lake should learn that lake management does not start a week before the beach opens. Rather, it begins when the water temperature reaches 13°C (65° F) because of problems associated with early blue-green algal blooms.

8- Where dredging spoils areas are steeply banked and dredging operation are expected to last several seasons, it is recommended that the dikes be mulched and seeded to prevent erosion.

Site Specific Recommendations

1- It is recommended that the aquatic plant survey be repeated in 1980 and 1981 to determine the final changes in the plant community due to dredging.

2- It is recommended that records be kept of future $KMnO_4$ treatments to determine if dredging lowers the demand for this chemical. Any long term reduction of demand would reflect a lowering of nutrient recycling in the system due to dredging.

3- It is recommended that the Town of Wellesley seek a user for the dredging spoils. If such a user can be found, then it may be possible to initiate a second round of dredging.

4- It is recommended that a shoreline management program continue for reduction of leaf loading for Morses Pond.

5- It is recommended that the planning go forward for the proposed modification of the existing dam. In this way, the door can be opened to use of winter drawdown as a weed control technique. This also allows drawdown before major floods, thus protecting the town's water supply wells from being flooded.

6- Finally, it is recommended that the Town of Wellesley attempt to manage Morses Pond without the use of alum. This recommendation is made because of potential problems from continued accumulation of alum floc.

Research Recommendations

1- It is important to note that the base flow quality of tributary streams differed from year to year. It is recommended that future research be conducted to determine what meteorological and/or groundwater conditions are responsible for these longer term variations in water quality. This is important for other lake studies where it may be necessary to use one year's data to predict the base flow component of the nutrient loading.

2- It is recommended that additional storms be monitored so that the relationships of storm loading to rainfall characteristics can be resolved. This is particularly true for the larger storms that are projected as having much greater nutrient loadings than smaller storms.

3- In monitoring additional storms, flow and nutrient monitoring during rainfall events of several days duration are needed for quantification of the nutrient loading for these extended periods of runoff.

4- It is recommended that the mathematics of storm loading be evaluated for small lakes. This means that for larger storms, some of the nutrient loading passes through the lake rather than interacting with the biological community in the lake. A method must be developed to quantify this phenomenon, especially for small lakes in relatively large drainage basins, in order to realistically model nutrient budgets.

2.0 THE LAKE AND ITS WATERSHED

Morses Pond in Wellesley, Massachusetts is located about 20 kilometers (12.5 miles) from downtown Boston. The community of Wellesley is almost completely developed and is considered one of the well-to-do suburbs of Boston. The main wave of development occurred in the late 1940's and 1950's. The town is almost totally served by sanitary sewers, but there still are some individual homes that are not connected to the sewer system. The homes closest to the lake began to be tied into the sanitary sewer system in the late 1970's. As of the report date, there are some 40 homes near the lake not connected to the sanitary sewer system, but 28 are on order of the Wellesley Public Health Department to connect.

The bedrock geology of the drainage basin as mapped by Nelson (1975) is entirely igneous and metamorphic. The Pre-Cambrian Dedham Granodiorite underlies most of the drainage basin with some areas of gabbro and diabase completing the igneous suite. The metamorphic rocks consist of quartzite and gneiss. There are no carbonate rocks in the drainage basin and thus the water is soft.

The surficial geology of the drainage basin as mapped by Nelson (1974) is mostly glacial tills and glacial lake deposits with some recent swamp deposits. In the immediate vicinity of the lake, the unconsolidated sediments are clearly dominated by glacial lake deposits. Till and some outwash deposits dominate the northern part of the drainage basin. Maximum thickness of unconsolidated sediments is about 60 feet, but bedrock does outcrop throughout most of the drainage basin.

The lake is a man-made lake. It was created some time prior to 1875 by damming a small stream. The pond was increased in size several times in its history and the last expansion flooded farm land and some wetlands. The pond was used for ice production until the mid-1920's when the advent of electric refrigeration destroyed the ice business. The pond was purchased by the town in 1931 and formal recreational use of the lake began in 1935.

Problems were noted in the lake in 1963 and Cortell (1964) conducted the first study of the lake. Algicide treatments began in 1967, and algal blooms could no longer be controlled by algicide use by 1973. The specific problem was repeated blooms of *Anabaena* sp. and *Aphanizomenon* sp. which prevented the lake from possessing the 1.25 meter (4 feet) visibility as required for public recreation by the Mass. Dept. of Public Health (1969). Note that the time from the start of algicide use to loss of recreational swimming in the lake was only 6 years.

Other studies were conducted by Allen (1973) and Camp, Dresser & McKee (1975). Kennedy (1975), Director of the Wellesley Department of Public Works, wrote the Board of Public Works stating that:

> "Since none of the past collected data can give the Department any direction for pond treatment during the coming summer, I am hopeful that the Board can give direction to the Department as quickly as possible."

This statement following three studies by three different groups clearly points to the status of lake management in New England in 1975.

Part of the lake's problems are related to the lake itself. The shoreline is relatively long relative to the lake's size and, there are four small islands and one large island which add to the total shoreline length. The lake outline and depth contours are shown in Figure 1; and Table 1 presents some statistics on lake properties. Figure 2 shows the generalized fair weather circulation pattern of the lake. When winds change, reversal or complete breakdown of this circulation pattern occurs.

The shoreline vegetation is largely deciduous trees. These trees add a considerable leaf load which helps color the water brown and adds to the organic sediments which support aquatic plant growth. The leaf load has not been quantified but a layer of leaves is easily seen in the coves in the fall of the year and leaves in various stages of decay are commonly recovered from most shallow areas of the lake during aquatic plant surveys.

The islands create two large isolated areas in the lake where protection from wave action plus the enhanced leaf loading has encouraged establishment of dense stands of aquatic plants. These plants, through the release of their metabolism by-products, add to the total nutrient load of the lake. In the past, when algal blooms were frequent, there was probably also a significant nutrient loading by direct release from the accumulated organic sediments due to low dissolved oxygen (DO) and associated pH-Eh cycles. There are no data available to document these conditons in the lake prior to the implementation of the actual restoration program.

Internal nitrogen loading by blooms of nitrogen-fixing blue-green algae was also a significant part of the total problem. This will be discussed quantitatively in a later section. When algal blooms did occur, there was probably also some hypolimnetic nutrient release from the deepest areas of the lake. In Morses Pond, the mixed layer in summer is generally between 3.5 and 4 meters (12 to 13 feet) thick. The hypolimnion generally occurs below 6 meters (20 feet) which means that less than one percent of the

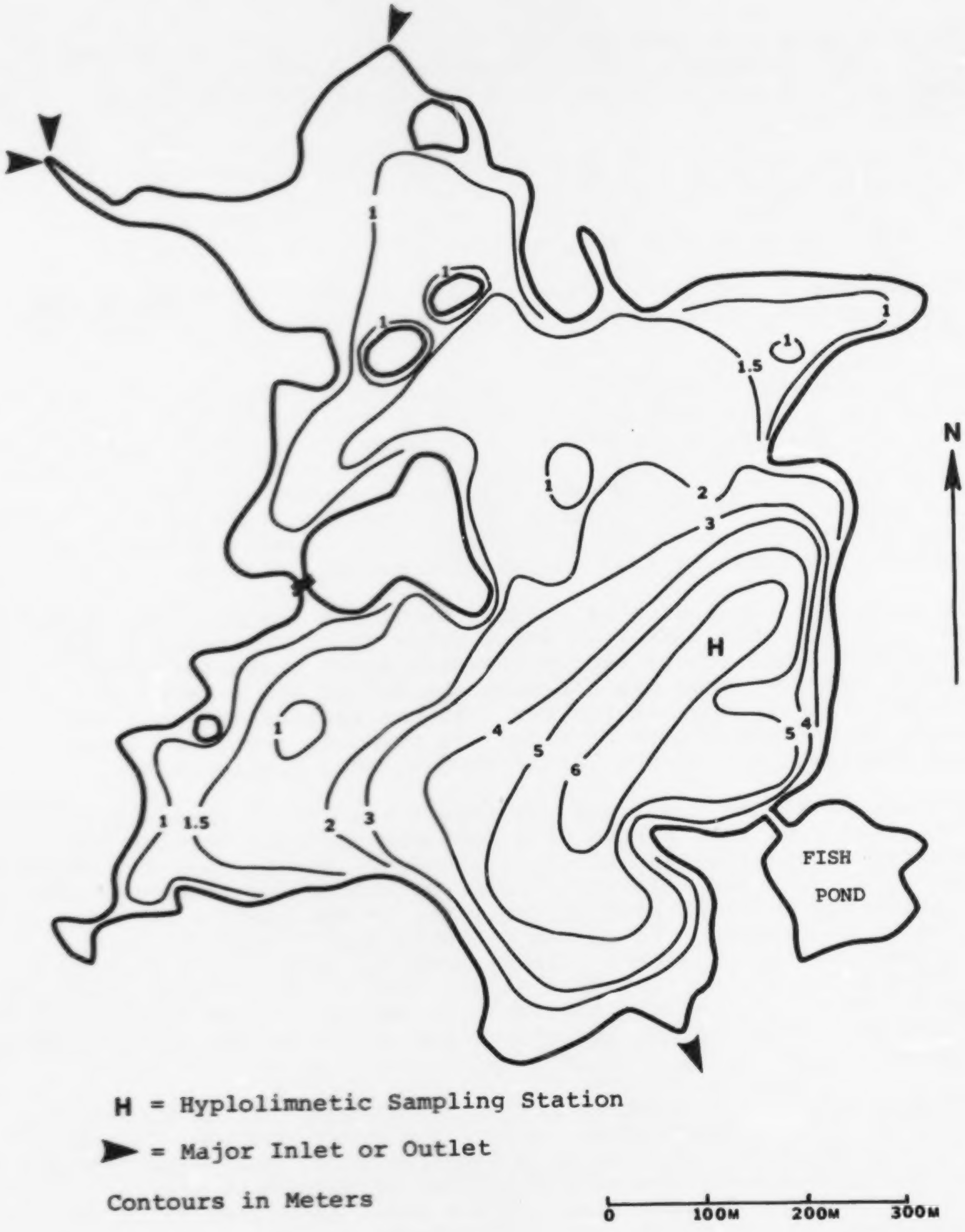
N
1
1
1
1.5
1
1
2
3
H
4
5
6
5
4
1
1 1.5
2
3
FISH POND
H = Hyplolimnetic Sampling Station
➤ = Major Inlet or Outlet
Contours in Meters
0
100M
200M
300M

Figure 1. Morses Pond Outline With Depth Contours

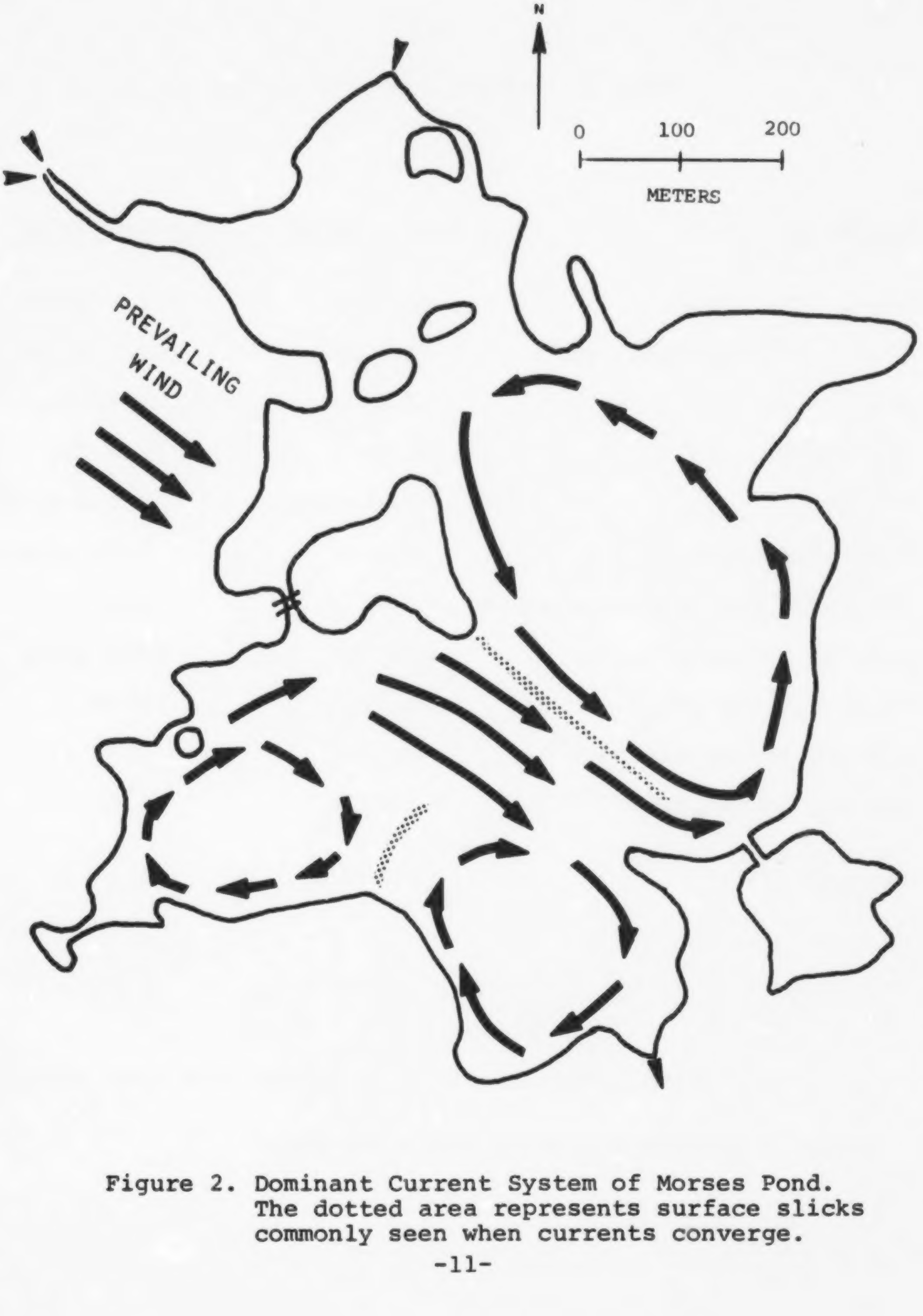
N
0
100
200
METERS
PREVAILING
WIND

Figure 2. Dominant Current System of Morses Pond. The dotted area represents surface slicks commonly seen when currents converge.

TABLE 1 MORSES POND STATISTICS

Parameter	Metric Units	English Units
Area, lake proper	41.5 ha	102.5 acres
Area including fish pond	43.3 ha	107.1 acres
Mean depth	2.36 m	7.74 ft
Max depth	6.95 m	22.8 ft
Volume	97.86 ha-m	793.4 acre-ft
Shoreline Length	5.8 km	3.63 miles
Shoreline Configuration ratio*	2.51	2.51
Area of Drainage Basin	2233 ha	5518 acres
Flushings per year	12.33	12.33
Average Annual Rainfall†	1.09 m	3.58 ft
Average Annual Runoff†	0.53 m	1.75 ft
Average Annual Lake Evaporation †	0.686 m	2.25 ft

* shoreline length - circumference of circle with area equal to lake area

† Values from Knox and Nordenson (undated).

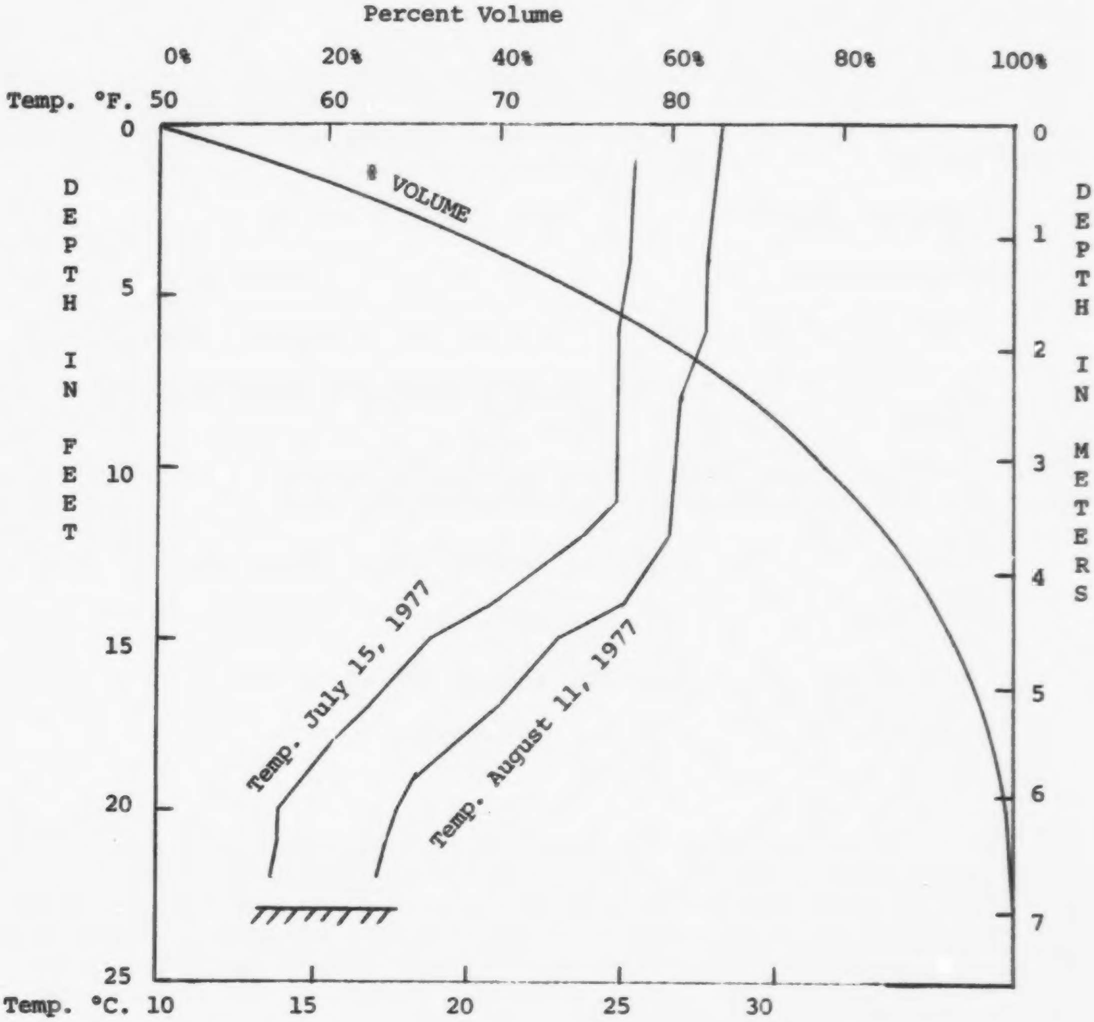

Figure 3. Typical Temperature Profiles and a Hypsographic Curve for Morses Pond. Figure 1. shows the location of the hypolimnetic sampling station where the curves were recorded.

lake's volume is involved with hypolimnetic nutrient recyling. Typical temperature profiles and a hypsographic curve are presented in Figure 3.

The character of the drainage basin clearly plays a role in the lake's problems also. The drainage basin is shown in Figures 4 and 5. It totals 2233 hectares (5518 acres) and consists of four sub-basins:

Boulder Brook	310 ha (765 acres);
Bogle Brook	1168 ha (2887 acres);
Jennings Pond Brook	494 ha (1220 acres); and

an area of 261 ha (646 acres) directly tributary to Morses Pond.

These various areas lie in four different towns. The areas by town and the associated status of sewering are:

Natick	782 ha,	75% of homes sewered;
Wayland	70 ha,	unsewered;
Wellesley	478 ha,	85% of homes sewered;
Weston	903 ha,	unsewered;
Total	2233 ha.	

The total developed area is about 40% of the drainage basin. Given that approximately 55% of the drainage basin area is not serviced by sanitary sewers, this is maybe part of the problem. However, most of this unsewered area is not adjacent to the lake. Thus, the existence of wetlands and other ponds upstream from Morses Pond means that these nutrient sinks act to reduce the impact due to lack of sewering

The general well-to-do character of the residential areas within the drainage basin is also part of the total problem. The residents in this area take pride in lawn care and heavy fertilizer use clearly adds to the problems in Morses Pond. Data on actual lawn fertilizer use in the drainage basin are not available nor has the impact of this use been specifically quantified for this study. Fall fertilizer applications are especially detrimental to the lake. Stewart et al (1975) have shown that over 50% of the nitrogen in fall fertilizer applications can be lost from the soil in eastern Massachusetts. This can adversely impact downstream water bodies, especially those that are nitrogen limited.

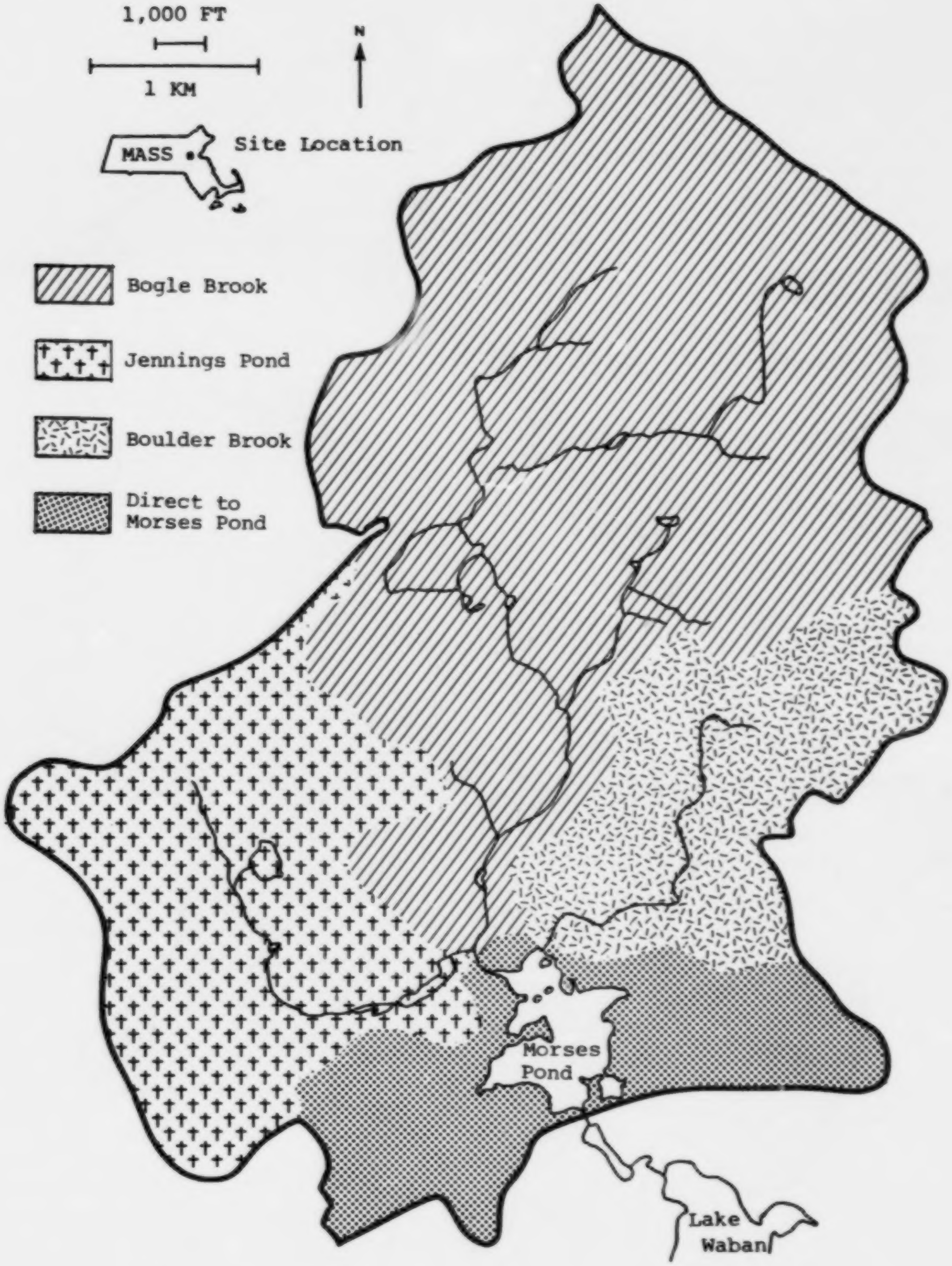
1,000 FT
1 KM
N
MASS
Site Location
Bogle Brook
Jennings Pond
Boulder Brook
Direct to Morses Pond
Morses Pond
Lake Waban

Figure 4. Morses Pond Drainage Areas.

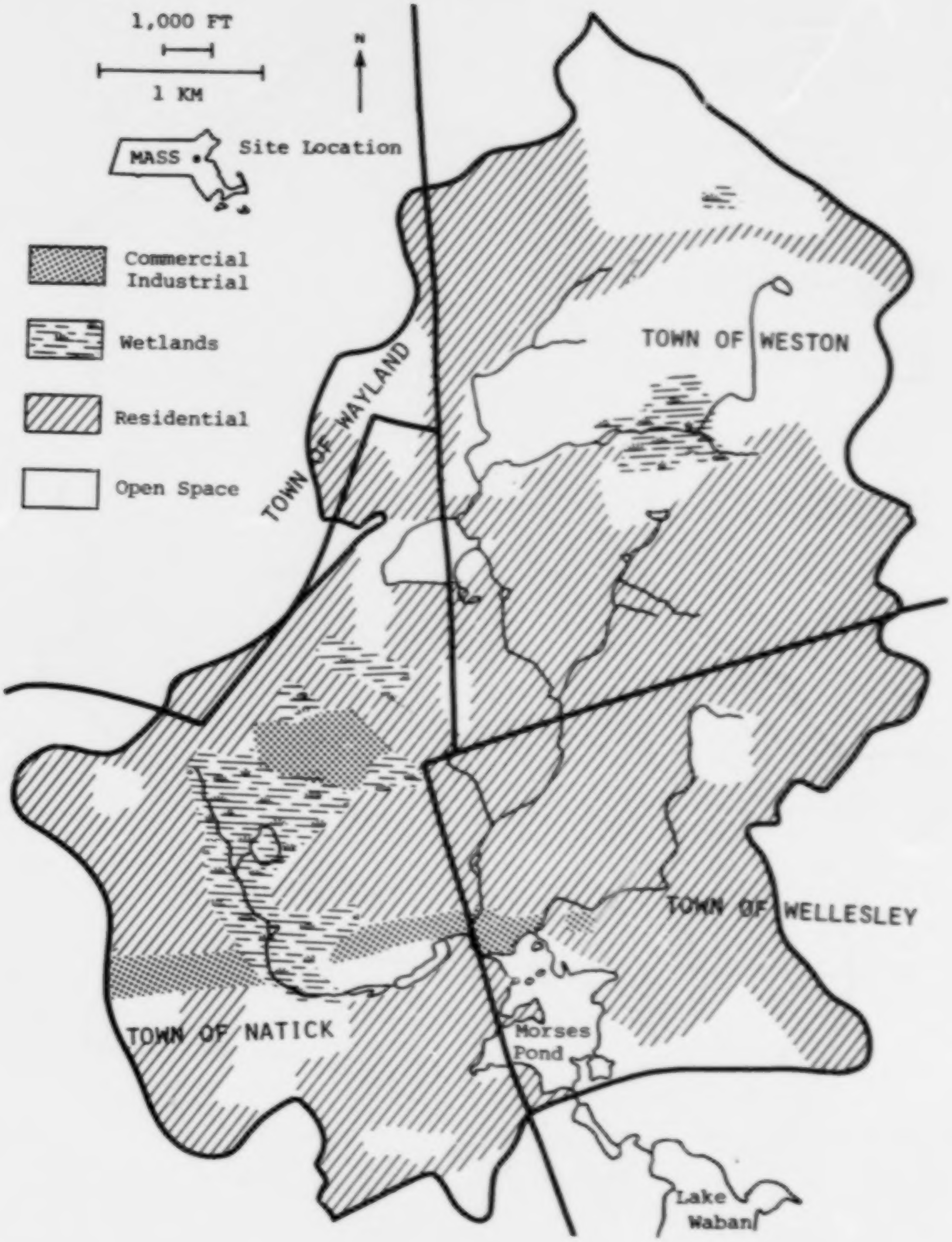
1,000 FT
1 KM
N
MASS
Site Location
Commercial Industrial
Wetlands
Residential
Open Space
TOWN OF WAYLAND
TOWN OF WESTON
TOWN OF WELLESLEY
TOWN OF NATICK
Morses Pond
Lake Waban

Figure 5. Morses Pond Drainage Area by Political Subdivision and Generalized Land Use. Land use data taken from the USGS topographic map of the Natick Quadrangle, 1970.

Another aspect of the total problem is Jennings Pond immediately upstream from Morses Pond. This 2.6 hectare (6.5 acres) pond is extremely eutrophic and is anoxic at depth in both summer and winter. Smells and odors produce frequent complaints near this small pond and when it overturns, significant nutrient loads arrive in Morses Pond. As an example of winter problems, on Feburary 24, 1977, a negative Eh of 70 millivolts was recorded at the outfall of Jennings Pond along with strong odor of hydrogen sulfide. Phosphorus values increased from 0.13 mg/l on January 26th to 0.45 mg/l on February 24th. This February value is almost double the value recorded in Bogle Brook on the same day. During normal periods, the nutrient concentrations in Jennings Pond and Bogle Brook are quite similar.

As an example of summer problems, Hurricane Belle passed near Boston in 1976. For the 5 days beginning August 6, 109.2 mm (4.30 inches) of rain fell. Jennings Pond overturned and the hydrogen sulfide released by the overturn was so strong that bacteria counts were requested just to see if a local sewage pumping station was leaking. The bacteria levels did not indicate any leakage of sewage. The net impact of the overturn plus the flushing of upstream wetlands, was that Morses Pond water turned a yellow-brown and blue-green algae that had been absent all Summer reached pre-bloom levels. It is surmized that the nutrient and iron associated with the strongly colored water triggered the algal bloom. Unfortunately, there was no chemical monitoring program in 1976 to document relative nutrient loadings due to the storm. It is clear, however, that restoration of Jennings Pond would help reduce the eutrophication of Morses Pond and the downstream Lake Waban.

Commercial and industrial land use is less than 2.5% of the drainage basin and there are no known point sources of pollution in the drainage basin. Agricultural land is also only a minor land use in the drainage basin.

3.0 THE INTEGRATED RESTORATION AND MANAGEMENT PROGRAM

The total program for the restoration and management of Morses Pond consisted of three phases. Phase I involved a one year program demonstrating that iron control would help block blue-green algal blooms. This initial phase was funded solely by the Town of Wellesley in 1975. Phase II consisted of eight tasks, the actual restoration and management efforts. These will be the topics of the discussion in the paragraphs that follow. Phase III of the program is the evaluation of the total program and this report is the main product of Phase III. The last two phases were funded 25% by the Town of Wellesley, 25% by the Massachusetts Division of Water Pollution Control and 50% by the U.S. Environmental Protection Agency under the Clean Lakes program 314(a). This original program was supplemented for additional dredging 50% by the Town and 50% by the EPA. Funding details for dredging will follow in a later section of this report.

The tasks under Phase II are:

Task #	Description
1	Leaf Load Reduction (Totally Town Funded)
2	Remove Emergent Vegetation
3	Control of Floating Leaf Plants
4	Public Education
5	Wetlands Protection
6	Periphyton Removal
7	Chemical Maintenance
8	Dredging

These tasks and their results are summarized below.

Task 1. Leaf Load Reduction

Management of leaf loading for lakes and reservoirs has been known to be important for decades. In the 1930's considerable effort was made, via federal work projects, to plant evergreens around reservoirs to protect water quality. The Office for Local Government, State of New York (1970) recommended planting with conifers as part of any reservoir management program and the U.S. Department of Agriculture (1971) recommended that no deciduous trees be planted within 20 feet of fish ponds. This task was funded solely by the Town of Wellesley and by volunteer efforts. Thus the town and the lake association have been implementing this task on their own, recognizing the long term value of reduced leaf loading to the lake system. The work under this task has involved removal of a few deciduous trees near the shore and the planting of pine seedlings by the town. Since this task is independently funded and since the task will take years to fully implement, there was no formal evaluation of this task under this research program.

Task 2. Remove Emergent Vegetation

The northernmost section of the lake, the area north of the two islands shown in Figure 1, was beginning to be converted to marsh by emergent vegetation. Major plants involved in various locations include sedge (Cyperaceae sp.), buttonbush (Cephalanthus occidentalis L.), purple loosestrife (Lythrum salicaria L.), arrow arum (Peltandra virginica (L.) Kunth.), cattail (Typha latifolia L.), and swamp loosestrife (Decodon verticillatus (L.) Ell.). While these plants dominate only 5% of the surface area north of the two islands, they were considered to be a major problem in the pond due to their rapid filling of the pond and due to potential nutrient release under the associated duckweed cover. Plant maps for dominant species are presented in section 6.3 of this report.

The solution to the emergent plant problem is removal of the emergent plants along with the organic sediments supporting their dense growth. In the earliest stages of Phase II, discussions included the concept of removal of these emergent plants by dragline. As the program progressed it was decided that removal was impractical by dragline because:

1- some of the plants were beyond the reach of a conventional dragline;

2- the shoreline character did not allow dragline access in some areas with our considerable shoreline modification; and

3- for those plants beyond the reach of a dragline, the plants may have been too much of a problem for a small dredge to deal with.

Thus, when other factors directed the program towards a more powerful dredge, the decision was made to perform Task 2 as an integral part of Task 8, Dredging. Therefore, the effectiveness of Task 2 will be discussed in the section on Task 8.

Task 3. Control of Floating Leaf Plants

This task involoves control of spatterdock (Nuphar variegatum Engelm.), white water lilies (Nymphaea odorata Ait.), and variable leaf pondweed (Potamogeton gramineus L.). Control of these plants is required because:

1- the plants interfere directly with recreation;

2- the metabolism by-products of the plants stimulate algal bloom problems, Novak et al (1975); and

3- these plants build-up bottom muck faster than the fully submerged aquatic plants due to their greater dry weight.

During 1977 and 1978, the only work under this task was to pick the flowers of the spatterdock and water lilies and physically remove some of the larger concentrations of variable leaf pondweed. The picking of flowers was done to reduce the seed population that would be exposed after dredging. It was also hoped that it would slow the spread of the water lilies in the pond. Once it was known what areas could be dredged with the limited dredging dollars available, the major effort under this task was aimed at removal of water lilies that lie outside the areas that were scheduled for dredging.

The work under this task was limited by the availability of manpower within the Wellesley Department of Public Works. It was even difficult to locate student labor for this task. However, several major concentrations of floating leaved plants were removed. During the post-dredging aquatic plant survey it was quite evident where the work had been terminated. There are no records available on the number or volume of aquatic plants removed under this task.

Task 4. Public Education

This task had three major goals. First, to keep the public informed about the program. This was partially achieved by cooperation with the staff of the local newspaper, The Wellesley Townsman, and by their news coverage of meetings of the Board of Public Works. In addition, meetings and presentations were held for the community at large and especially for the lake association. This task ensured that the public was informed and had a chance for input into the program before final decisions were made.

The second goal of this task was to get lake shore residents involved in the total program. As the program got underway, two essentially defunct lake associations were reactivated and merged into one more active group, the Morses Pond Association. They supported the program at various public hearings and encouraged the town to add new funds to expand the level of the dredging effort. In addition, the new and more active lake association began to hold annual lake shore clean-up days where debris was removed from private lands and public access areas. In addition, deciduous trees were cleared along some public shoreline areas. Shoreline residents were also educated about such mundane matters as why they should not throw leaves and lawn clippings into the lake, why reduce fertilizer use, and perhaps most importantly, why tie into the recent extension of the sanitary sewer system. Given that the lake shore residents could see an improved water quality via the chemical management program, they generally accepted the Wellesley Health Department directive to tie into the sanitary sewer system. For another eutrophic lake in town that is not being managed, the same directive produced a strong public resentment and threats of legal action.

The third goal of this task was to reduce fertilizer use an lawns in the drainage basin. Control of lawn fertilizer use was deemed an important part of this total program because:

- nitrogen control is the thrust of this entire lake management program;
- unconsumed inorganic nitrogen as nitrate or ammonia can pass freely through the soil (Uttormark et al, 1974) and thus enter downstream lakes via groundwater discharges into the lake or the tributaries that feed the lake; and
- timing and doses of lawn fertilizer application favor losses to surface and ground water systems.

To achieve this goal and re-enforce the other goals of this task, the following public education activities were undertaken:

- seven lectures were given to various civil groups, school groups, and at public hearings;
- newspaper articles by Lent (1977) and Chagnon (1978) were published in The Wellesley Townsman and which were later republished in other local papers;
- these articles and an associated news release triggered articles by Kornfield (1977) and Quill (1978) in the Boston Herald American and the Boston Globe respectively which stressed the reduction in lawn fertilizers and reclaimation of Jennings Pond;
- over a two-year period the Department of Public Works

sent out fliers with utility bills on reducing fertilizer use because of impacts on Morses Pond;

- a letter was sent out to lawn care firms recommending proper fertilizer application practices; and
- materials were supplied to other groups involved with public education relative to Morses Pond.

There has been no follow-up program as part of this project to measure the effectiveness of the public education program. What can be said on a subjective basis is that after the first year of public education the observed biomass of the submerged aquatic weeds in 1977 was less than the amount observed in 1975. Water milfoil that formerly reached the surface over extensive areas of the pond, no longer reached the surface of the lake as it did in 1975 when there was no public education program. Unfortunately, we have no definitive proof that reduced fertilizer use was responsible, or even contributory to the apparent reduction in aquatic plants.

Task 5. Wetlands Protection

Immediately north of the lake there are two major wetlands as shown in Figure 6. The first of these wetlands is a channelized marsh where it is postulated that nutrient consumption in the summer would act to protect the lake. The land was largely owned by a land speculator who purchased the land thinking it would someday be zoned commercial or be suitable for residential development. Thus the owner was seeking an unreasonable price for the marsh and the land was not purchased by the town. However, Massachusetts has a strong state wetlands program and the wetland was restricted for development. Thus the pond-wetland relationship will be protected as long as the state Wetlands Restriction Law (Mass. General Law, C.131, Section 40A) is upheld. The funds allocated for the purchase of this wetland were diverted into the dredging portion of the program.

The second wetland is approximately 4 acres of wooded swamp that lines both sides of Boulder Brook for a distance of 365 m (1200 ft.). This second wetland is separated from the wetland described above by a narrow band of residentially developed land. The owner of the second property had already signed a purchase option with a developer, the land being partially wetland and partially upland. When the developer realized that he could not work in the wetlands due to a strong Conservation Commission, he dropped the entire project. Note that in Massachusetts, the Conservation Commissions are town boards and are the enforcing agents of the state's Wetlands Protection Act (Mass. General Law, C131, Section 40) (not to be confused with the aforementioned Wetlands Restriction Act). After the purchase option expired, the town was

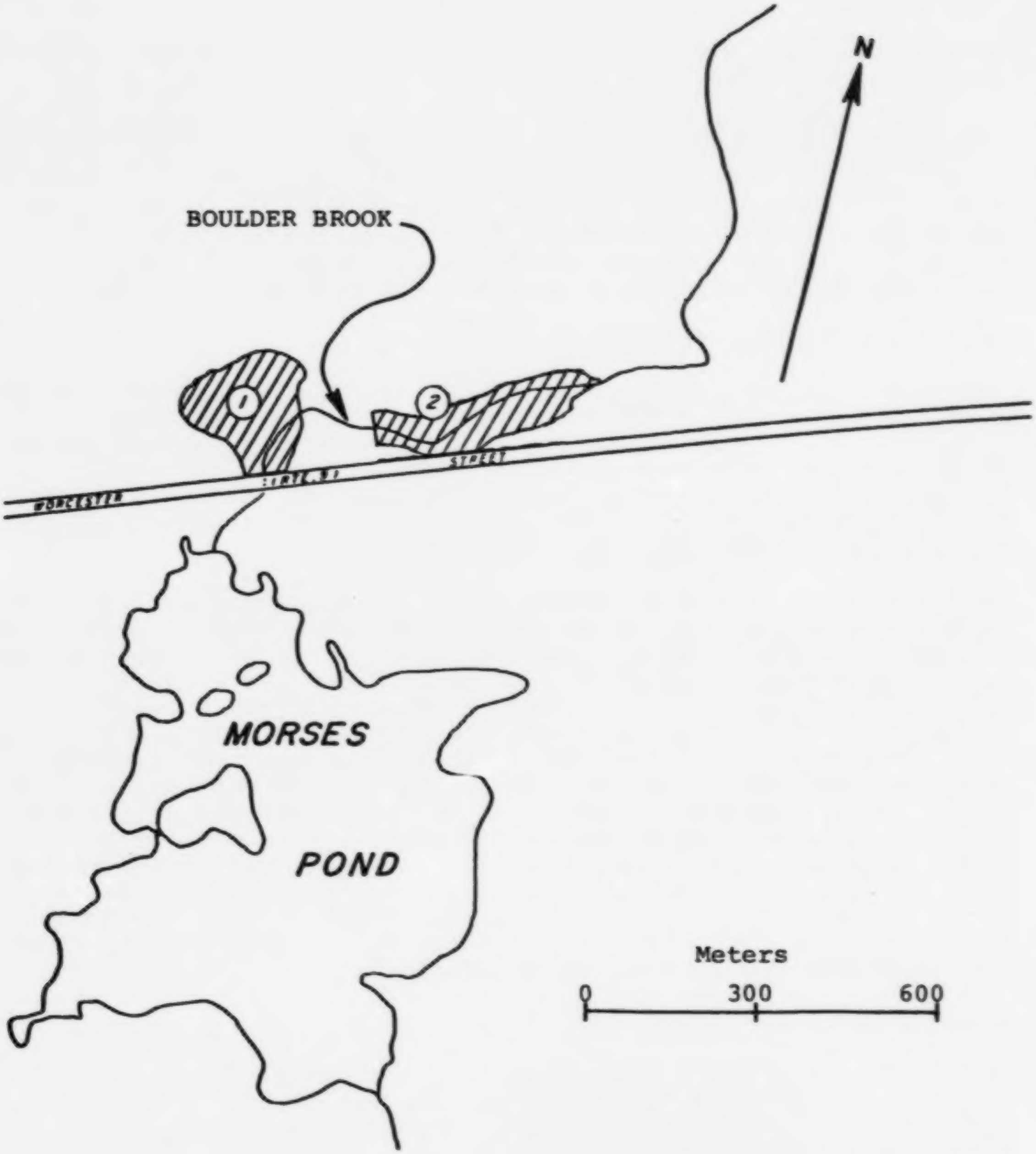
N
BOULDER BROOK
1
2
WORCESTER
(RTE. 9)
STREET
MORSES
POND
Meters
0
300
600

Figure 6. Key Wetland Areas. Wetland 1 is an emergent open marsh and wetland 2 is a band of wooded swamp along the stream edge. Figure from aerial photos.

able to purchase the land under this program for the fair market value of the land.

The protection of this wetland is important for two reasons. One, because the shaded nature of the stream makes it the only cool water tributary which lowers heat load to the pond and offers a cool water habitat. Two, because protection of the site from development blocked significant erosion during construction and blocked long term nutrient loading that would result from post-development impervious surfaces and excessive lawn care.

Task 6. Periphyton Removal

Periphyton is used here in the widest sense to mean sessile algae found on, or attached to, any substrate. The main periphyton in Morses Pond is *Schizogonium* sp. This algae covers the mud bottom as a thick mat in places and also grows as fibers over water milfoil and other submerged aquatic plants. The algae is known to occur in nearby Lake Cochituate, which is also eutrophic and may be nitrogen limited according to its N/P ratio.

In years prior to and including 1975, the *Schizogonium* algal mats have risen to the surface of the lake during sustained periods of hot weather, >35°C (95°F). The rising is caused by trapped gases generated either as metabolism by-products of the algae or by decay of underlying leaves, organic debris and accumulated periphyton. Once at the surface, the periphyton drifts around the lake interfering with boating, littering beaches, and totally clogging isolated coves. When total coverage is achieved in some larger coves, anaerobic conditions develop under the periphyton mat and complaints about smells and odors are common. Given all these problems, Task 6 was aimed at removal of periphyton if and when it rose to the surface again. In the three summers since Phase II was initiated, the periphyton never rose to the surface in significant quantities. Since there was no problem, the money for this task was diverted to dredging.

Task 7. Chemical Management

Task 7 is of critical importance to the program. This task involves the routine management of nitrogen in this nitrogen limited lake. Note that this task is unique in all the 314(a) Clean Lakes Program because:

1- it is the *only* program where nitrogen control is the focus of lake restoration and management;

2- it is the *only* program demonstrating that internal nitrogen loading via nitrogen-fixation can, in fact, be controlled;

3- it is the only program where potassium permanganate ($KMnO_4$) is being used in the open lake waters for nutrient inactivation; and

4- it is the only program where control of iron as a micronutrient is an essential part of the total management program.

The fundamental theory behind use of $KMnO_4$ for control of blue-green algae was derived from work by Morton and Lee (1974) combined with the well known use of $KMnO_4$ to remove iron from drinking water; Haney (1964), Humphrey and Erkleberry (1962), and Willey and Jennings (1963). Since the article by Morton and Lee is so important, the article is reproduced herein as Appendix A, with the kind permission of the American Chemical Society.

At this point it is necessary to describe the details of the theory that has been field tested during this research and demonstration project. This theory involves:

- potassium permanganate's role in removal of iron from aquatic systems;
- the effect that iron removal has on inhibiting nitrogen fixation by blue-green algae; and
- the return of a phytoplankton community to dominance by green algae by eliminating the advantage blue-green algae have via their ability to fix nitrogen in nitrogen limited systems.

These items are addressed below.

Let us first look at the basic concept of iron deficiency in plants. Iron deficiency is a well known phenomenon in agriculture, Viets and Hanway (1957). Iron function in plants is essential for the formation of chlorophyll. In plants, the complex iron compounds regulate respiration in plant cells through their associations with enzymes, Wadleigh (1957). Thus it is easy to see that iron deficient environments have the potential to significantly impact all plants. In terms of phytoplankton, where the cells are short lived and must draw all their nutrients from the supporting water, iron deficiency has the potential to affect the growth of all classes of these organisms.

In terms of the nitrogen fixing blue-green algae, iron is essential for nitrogen fixation, Trainor (1978); as are boron, calcium, cobalt, and molybdenum. The nitrogen fixing enzyme, nitrogenase, can be fractionated into two components; one of which contains molybdenum and iron and is designated the Mo-Fe protein, and the other contains iron and is designated the Fe protein, Hardy and Havellsa (1975). The Mo-Fe protein contains 17 to 36 iron atoms per protein molecule while the Fe protein contains 4 iron atoms per protein molecule. The theory basic to this project is that in an iron deficient environment, this heavy demand for iron cannot be satisfied and nitrogen fixation should be inhibited or blocked. The reduced capacity to fix nitrogen in a nitrogen limited system would thus reduce the competitive advantage blue-green algae would have over green algae. The experiments described in Appendix A substantiates the general theory while this research project is designed to seek further substantiation in a complex real world environment.

In a more graphic sense, the step from dominance by blue-green algae to green algae, via iron stripping of lake water, may be pictured using a catastrophy theory diagram, after Zeeman (1976). Such a diagram is shown in Figure 7. This figure shows that once sufficient iron is present, the algal dominance will fall off the green algae surface to the blue-green surface (X to Y via AB). Once on the blue-green surface, blue-green algal dominance will be maintained given small reductions in iron. However, given a dramatic decrease in iron, such as caused by $KMnO_4$ treatment (Y to X via CD), the behavior pattern will return to the green algal dominance surface and will remain on that surface even when small increases of iron occur. Results supporting this theory will be discussed in the section of the report on algal community behavior.

Given this background, the essential components of the total chemical management program and the purpose of each step is as follows:

1- $KMnO_4$ is used once at the start of each season as the water temperature begins to approach 20°C (68°F) to:

   a- convert the soluble and organic iron in the lake into iron oxide that is not available for biological consumption unless resolution occurs; and

   b- oxidize organic complexes (large organic molecules) that discolor the water and act as algal growth stimulators, Kappe and Kappe (1971).

   Minor benefits of $KMnO_4$ include:

   a- increasing the dissolved oxygen content at depth and thus temporarily reducing any hypolimnetic nutrient release associated with anaerobic conditions;

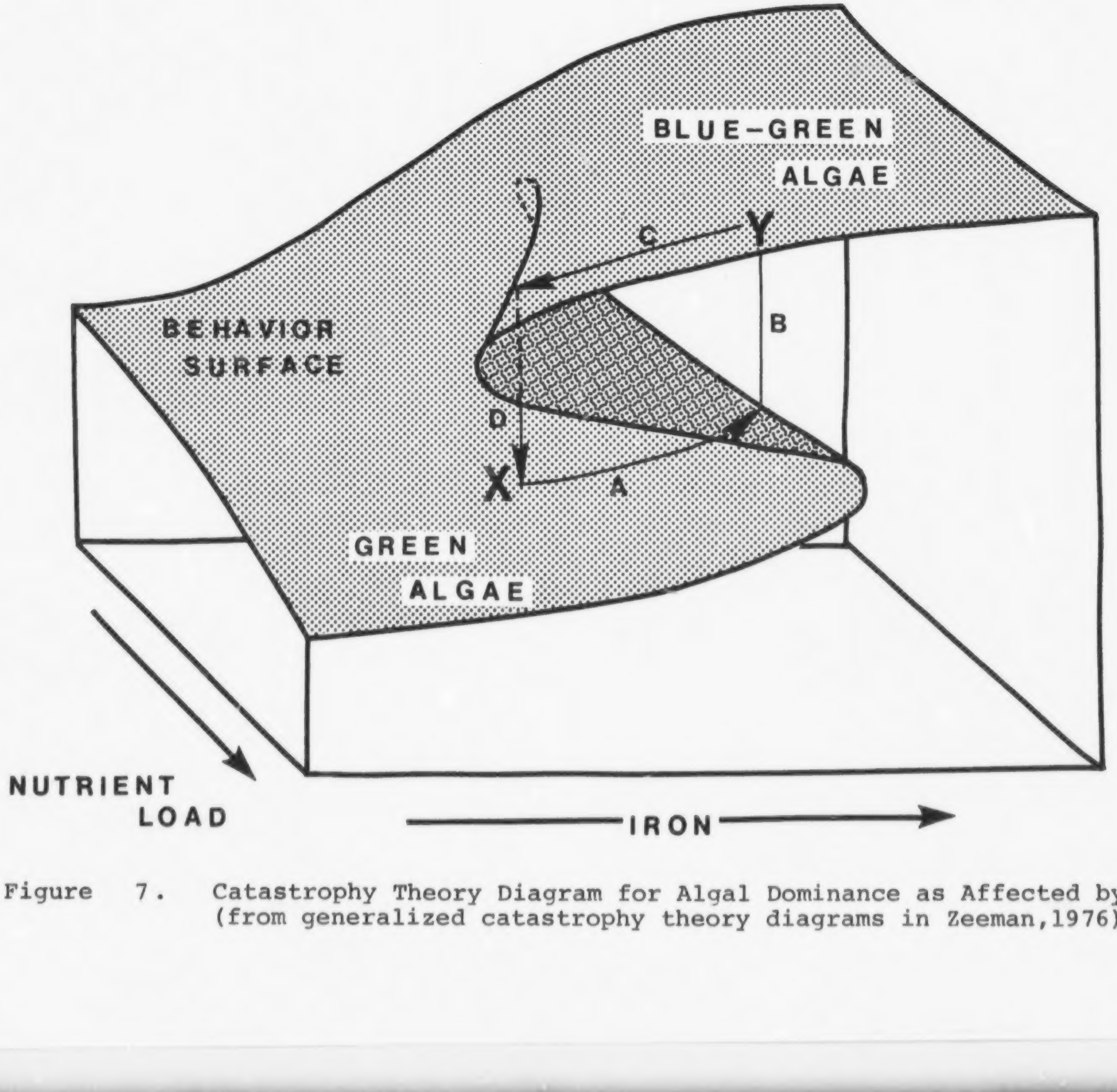
BLUE-GREEN
ALGAE
BEHAVIOR
SURFACE
GREEN
ALGAE
Y
X
A
B
C
D
NUTRIENT
LOAD
IRON

Figure 7. Catastrophy Theory Diagram for Algal Dominance as Affected by Iron (from generalized catastrophy theory diagrams in Zeeman,1976).

b- possible oxidation of the surface layer of organic sediments, thus further reducing internal nutrient recycling in the lake; and

c- an immediate reduction in total nitrogen available in the lake.

Details of this latter phenomenon are discussed later in this report.

2- Alum is used as part of the chemical management program. Alum is used to:

a- clear the residual MnO_2 left by the $KMnO_4$ treatment;

b- generally clear the water of suspended matter; and

c- temporarily remove algae by chemical coagulation.

Secondary benefits of alum include:

a- removal of phosphorus by chemical adsorption;

b- suspected removal of other micro-nutrients by adsorption; and

c- the accumulation of alum on the bottom of the lake may inhibit phosphorus release from the bottom sediments.

3- $CuSO_4$ is used on an as-needed basis as part of the chemical program. It is used for elimination of seed populations of blue-green algae prior to $KMnO_4$ treatments and to deal with any pre-bloom conditions that may evolve in the phytoplankton community as the recreation season progresses.

It should be noted that in 1973, seven $CuSO_4$ treatments plus one Hydrothol-47 treatment in the beach area failed to control the blue-green algal blooms. $CuSO_4$ doses applied were 0.6 and later 0.8 mg/l for *Anabaena* and *Aphanizomenon* respectively. This early work shows that $CuSO_4$ is not, in itself, sufficient for algal bloom control. In 1974, while $CuSO_4$ plus alum successfully inhibited repeated blue-green algal blooms, the blue-greens did continue to remain at bloom threatening levels for most of the recreation season. Once $KMnO_4$ was added to the chemical management program, blue-green levels dropped significantly and total control was achieved, with occasional $CuSO_4$ use. $CuSO_4$ doses applied from 1975 to 1979 were 0.3 mg/l for *Anabaena* and 0.5 mg/l for *Aphanizomenon* as generally recommended by Hale (undated). Control was complete at these levels with the $KMnO_4$ use. One reason for greatly improved control with the new chemical program is that $KMnO_4$ eliminates the organic complexes that chelate copper thus improving the effectiveness of $CuSO_4$ treatments.

One key concern in this total program is to separate the effects of alum from those of $KMnO_4$. This is especially important because of the over-emphasis on the role of phosphorus management in limnology today. Because of this over-emphasis, some individuals may believe that the benefits achieved in this program are due to alum and not to $KMnO_4$. Fortunately, there are two sets of data that allow clarification of this issue. The first set of data is from Morses Pond itself in 1974. This data set represents a period from mid-July to Labor Day when the lake was influenced by alum and $CuSO_4$. These data allow comparison with the recreation seasons 1975 to 1979 when $KMnO_4$ was used with alum and $CuSO_4$. Table 2 presents the 1974 versus the 1975 to 1979 data.

The second data set that documents the effectiveness of $KMnO_4$ alone is from Pillings Pond in Lynnfield, Mass. This pond has the following similarities and differences when compared to Morses Pond.

Similarities:

- Both ponds are shallow.
- The areas are similar, 39.5 ha. to 41.5 ha.
- Both ponds were nitrogen limited prior to treatment. For Pillings Pond N/P = 10.7 in late spring before nitrogen fixation balances the N/P ratio. Morses Pond N/P ratios are discussed in a later section in detail.
- Both ponds have histories of blooms of _Anabaena_ and _Aphanizomenon_.

Differences:

- Areal coverage by white water lilies and spatterdock was greater in Pillings Pond.
- Extensive cover of duckweeds and floating colonies of blue-green algae in the isolated coves of Pillings Pond had the potential to induce significant internal nutrient recycling due to the pH-Eh regime. While pH and Eh were not measured under this cover in Pillings Pond, the significant and frequent hydrogen sulfide odors from the pond clearly demonstrate reducing conditions in Pillings pond.

Table 2. Post $KMnO_4$ Treatment - Surface Phytoplankton and Visibility Statistics for Morses Pond, 1974 - 1979. See Appendix C for Discussion on Sampling.

	1974	1975	1976	1977	1978	1979ξ	1979Ψ
Mean Total Algal Counts(ASU/ml)	1274	167	792ζ	808	155	1743	2863
Mean Blue-Green Algae (ASU/ml)	219	14.4	30.1	77.0†	4.3	1231	2309
Mean *Anabaena* (ASU/ml)	7.0	1.1	5.4	9.3§	1.1	3.4	203
Mean *Aphanizomenon* (ASU/ml)	46.5	0.06	7.6*	0	0	0	5.1
Mean Visibility After Combined Treatments [m/(ft)]	1.7 (5.5)	3.3+ (11.0+)	4.1+ (13.3+)	3.1+ (10.3+)	3.4+ (11.2+)	3.7+ (12.1)	2.3 (7.5)
Number of Sampling Events	14	38	59	36	33	27	13

* *Aphanizomenon* was not present until a major storm occurred in August. Visibility dropped about one meter and the water turned a yellowish brown indicating significant iron additions. Then *Aphanizomenon* appeared a few days later at significant levels.

ζ The 1976 $KMnO_4$ treatment was in early May, thus statistics include a late Spring period of enhanced productivity. In most other years, the treatment was delayed until June by cooler weather and this late Spring productivity was not included in the statistics.

† The 1977 algal counts generally ran higher than those of 1975. *Anabaena* was left in the lake longer at the start of the season and this combined less nutrient consumption in the smaller watermilfoil crop could have generally encouraged phytoplankton.

§ 1977 data included values from a pre-bloom condition that was allowed to exist in the lake for 18 days. In 1975 and 1976, this pre-bloom condition was not allowed.

ξ Dredge working in an isolated part of the lake prior to August 2nd.

Ψ Dredge working in the main circulation patterns of the lake after August 2nd. (See Figure 2.)

+ The plus sign indicates that numerous readings gave values where the secchi disk was visible on the bottom in about 4 meters (13 feet) of water. Thus the true mean is greater than the value shown. See Appendic C for discussion of visibility sampling.

- The magnitude of the algal blooms in Pillings Pond was much more severe with a maximum value of 72,000 ASU/ml versus 3,200 ASU/ml for blooms in Morses Pond.

The massive algal blooms in Pillings Pond continued over the past years even with attempted control with $CuSO_4$. In 1979, $KMnO_4$ was used _without_ alum. $CuSO_4$ was used to deal with pre-bloom levels of blue-green algae. No odor problems developed and blue-green algal counts decreased significantly. Both data sets clearly point to the effect of iron stopping by $KMnO_4$ on blue-green algae. Summary analyses from Pillings Pond are presented in Table 3. Unfortunately, in the case of Pillings Pond there is no simultaneous chemical data for 1979.

TABLE 3. PHYTOPLANKTON STATISTICS AT THE SPILLWAY OF PILLINGS POND, LYNNFIELD, MASS. 1977 and 1979. All units in ASU/ml. Spillway samples represent open water of the main body of the lake.

	1977 No Treatment	1979 $KMnO_4$ Treatment
Average Total Algae	52,507	49,850*
Average Blue-Green	27,930	4,537
Average _Anabaena_ sp.	6,993	597
Average _Aphanizomenon_ sp.	14,276	262
Number of Samples	3 (August only)	13

* Note that in 1979, winter drawdown had occurred and white water lily and spatterdock rhizomes were drifting about the pond releasing decay products that stimulated total algal growth.

The issue of $KMnO_4$ as an algicide also has to be addressed. This issue has two related components. The first is the actual ability of $KMnO_4$ to toxically affect algal populations at low doses. The second issue is the well known, but poorly understood, ability of manganese in solution to inhibit growth of blue-green algae.

The studies by Fitzgerald (1964, 1966) and Hemp (1966) involving $KMnO_4$ are quite different in nature from the in-situ programs conducted in Morses Pond and Pillings Pond. The major differences are:

1- the dose rates were 1 to 64 mg/l in the toxicity tests while in the field tests all doses were just enough to satisfy the ten minute $KMnO_4$ demand of the water, i.e., less than 3 mg/l.

2- the water used in the reference tests was distilled water spiked with algal growth media while raw lake water was obviously used in the field tests.

The net result of these two differences was that in the toxicity tests there was residual $KMnO_4$ in the water during the tests while there was no residual $KMnO_4$ in the field tests. This means that in the field tests, there is minimal algal-$KMnO_4$ contact time while the $KMnO_4$ is rapidly being eliminated by interactions with organic compounds in the water. It is the lack of residual $KMnO_4$ in this field program that clearly differentiates these field tests from the laboratory toxicity tests.

Actual field results for the algal community response to the 1977 $KMnO_4$ treatment (average dose 1.3 mg/l) are presented in Table 4. This year was selected because in other years blue-green algae were not present at the time of treatment or because a copper sulfate treatment had occurred a few days before the $KMnO_4$ treatment. The data in Table 4 show that 40 hours after the $KMnO_4$ treatment algal biomass had increased, blue-green algal counts had increased in both biomass and colony counts, and that total species present increased. One or two minor species were not reported after $KMnO_4$ treatment but such variations in minor species is an everyday occurrence. Since algal counts, biomass and number of species all decrease with algicide treatments, the conclusion is inescapable that the $KMnO_4$ is not an algicide at low doses. Since the $KMnO_4$ chemical reaction leaves zero active $KMnO_4$ in the water after a few hours, it is impossible that there are long term algicidal effects because the chemical is gone.

As for inhibition of blue-green algae by residual manganese, this requires that the manganese be present in soluble form. When $KMnO_4$ is used the pertinent chemical reactions reported by Posselt (1968) are:

$$MnO_4^- + 2H_2O \rightarrow MnO_2 + 4OH^- \qquad (1)$$

$$3Mn^+ + 2MnO_4^- + 2H_2O \rightarrow 5MnO_2 + 4H^+ \qquad (2)$$

Note that in the first equation all the manganese in $KMnO_4$ is converted to manganese dioxide (MnO_2) which is insoluble (Weast, 1979). Note further in the second equation that all soluble manganese present is also converted into insoluble MnO_2. Thus treatment by $KMnO_4$ decreases the potential for manganese inhibition of blue-green algae by conversion of all effective manganese into insoluble forms. In addition, alum treatments a few days after $KMnO_4$ treatments remove the MnO_2 by coagulation. Thus there is neither soluble, nor significant insoluble manganese present in Morses Pond to act as algal growth inhibitors.

It has been demonstrated that that $KMnO_4$ is not an algicide at low doses, nor an inhibitor of blue-green algae. These facts, combined with the information in Appendix A, leaves a reasonable working theory that induced iron deficiency is responsible for the reduced populations of blue-green algae seen in lakes treated with $KMnO_4$. It is predicted that additional laboratory and field testing under controlled conditions will verify this theory.

Task 8. Dredging

The purpose of this task was to eliminate nutrient recycling from aquatic plants and organic sediments as well as block the spread of emergent plants into the area north of the two islands. The character of the organic muds is defined in Appendix D.

The major problem areas in the pond were divided into 5 areas for dredging. These 5 areas are shown in Figure 8 and are defined below.

Area I -Dredging would eliminate significant stands of spatterdock and emergent plants. A cut of 0.6 m (2 feet) will expose sand and gravel bottom over most of the area.

Area II -Dredging would eliminate dense stands of submerged and floating leaf plants. An average cut of 0.9 m (3 feet) will expose sand and gravel bottom over most of the area.

Area III -The area is very densely covered with aquatic weeds. Unfortunately, the organic sediments are over 2.1 m (8 feet) thick in places. Thus, a cut of 0.45 m (1.5 feet) was proposed to eliminate the present plant problems and the mucky surficial layer of sediments.

Area IV -This area is beginning to become clogged with

Table 4 . Algal Counts from Morses Pond before and after Potassium permanganate treatment, May 27, 1977. See Text for discussion. All algal units in ASU/ml. numbers in parentheses are colony counts per 100 ml. All genera had only one species present.

	BEFORE		AFTER	
	May 26, 1977		May 29, 1977	
	Cloud Cover 100% Air Temperature 17.8°C. Water Temperature 21.1°C. Moderate Breeze		Cloud Cover 30% Air Temperature 15.5°C. Water Temperature 22.2°C. Light Breeze	
Station	B	D	B	D
GREEN ALGAE				
Chlorella	-	7	7	-
Closterium	-	-	-	4.2
Coelastrum	-	-	-	15
Gloeocystis	-	-	7	-
Golenkinea	-	-	8.4	10
Oocystis	-	-	-	1.4
Schroederia	7	4	-	4.2
Sphaerocystis	-	-	28	46
Staurastrum	4	-	1	5.4
Westella	48	11	37	7
Unknown	4	-	-	-
TOTAL GREENS	63	22	88.4	93.2
PIGMENTED FLAGELLATES				
Chlamydomonas	-	-	-	0.7
Lepocinclis	50	-	23	21
Mallomonas	50	35	156	94
Uroglenopsis	-	-	6	-
Unknown 1	-	11	2.8	2.8
Unknown 2	-	0.7	-	-
TOTAL FLAGELLATES	100	46.7	187.8	118.5
BLUE-GREENS				
Anabaena	1 (3)	1.3 (4)	22 (10)	22 (10)
Anacystis	8	10	91	35
Oscillatoria	-	-	-	24
TOTAL BLUE-GREENS	9	11.3	113	81
DIATOMS				
Asterionella	45	39	-	21
Cymbella	-	-	-	4.2
Frustulia	-	-	21	17
Gomphonema	4	-	-	-
Rhizosclenia	1.4	-	-	-
Stauroneis	-	-	-	1.5
Synedra	-	-	-	2.6
Tabeliaria	-	-	17	12.4
TOTAL DIATOMS	50.4	39	38	58.7
TOTAL ASU/ml	222.2	119.0	427.2	351.4
TOTAL SPECIES	11	10	15	20

submerged and floating leaf plants. A 0.9 m (3 feet) cut will expose a sand and gravel bottom.

Area V -This area is similar to Area III, but with a less dense weed population and with organic sediments exceeding 4.3 m (14 feet) in thickness.

Based on the fact that funds for dredging were limited, the areas above were assigned the following priorities:

Highest Priority - Area I;
- Areas II and IV (about equal);
- Area III
Lowest Priority - Area V.

Given the limits of funding, Areas III and V were not dredged at all and almost half of Area II was not dredged.

The portable hydraulic suction dredged used was a 12" AMMCO dredge with a 740 horsepower pump, a 42" cutterhead and a 55' ladder. Operation of a large dredge is done in long linear paths, the position of the dredge being controlled by anchors and cables. Given that the water was so shallow, the initial run of the dredge began in Area II and progressed to Area I as shown in Figure 9. The second run was set at the limits of Area I. Thereafter, dredging runs were set in Areas I, II and IV depending on (1) dense population of floating leaf and emergent plants, (2) limits of dredge operational capability, and (3) recreational values.

The limits of the final dredging are shown in Figure 9.

The various items that were learned in this dredging program include the following:

1- The size of the spoils area is critical to any dredging operation. Wellesley lost about 13% of its designed volume during construction due to desires to save some trees. This reduced the final dredging volume.

2- Control of turbidity in discharges from the spoils area is a significant problem.

3- Sand filter control of turbid water is possible but small sand filter areas plug up too fast for economic dredging.

4- Alum treatment and batch releases of water from the spoils area give good control of turbidity and nutrient

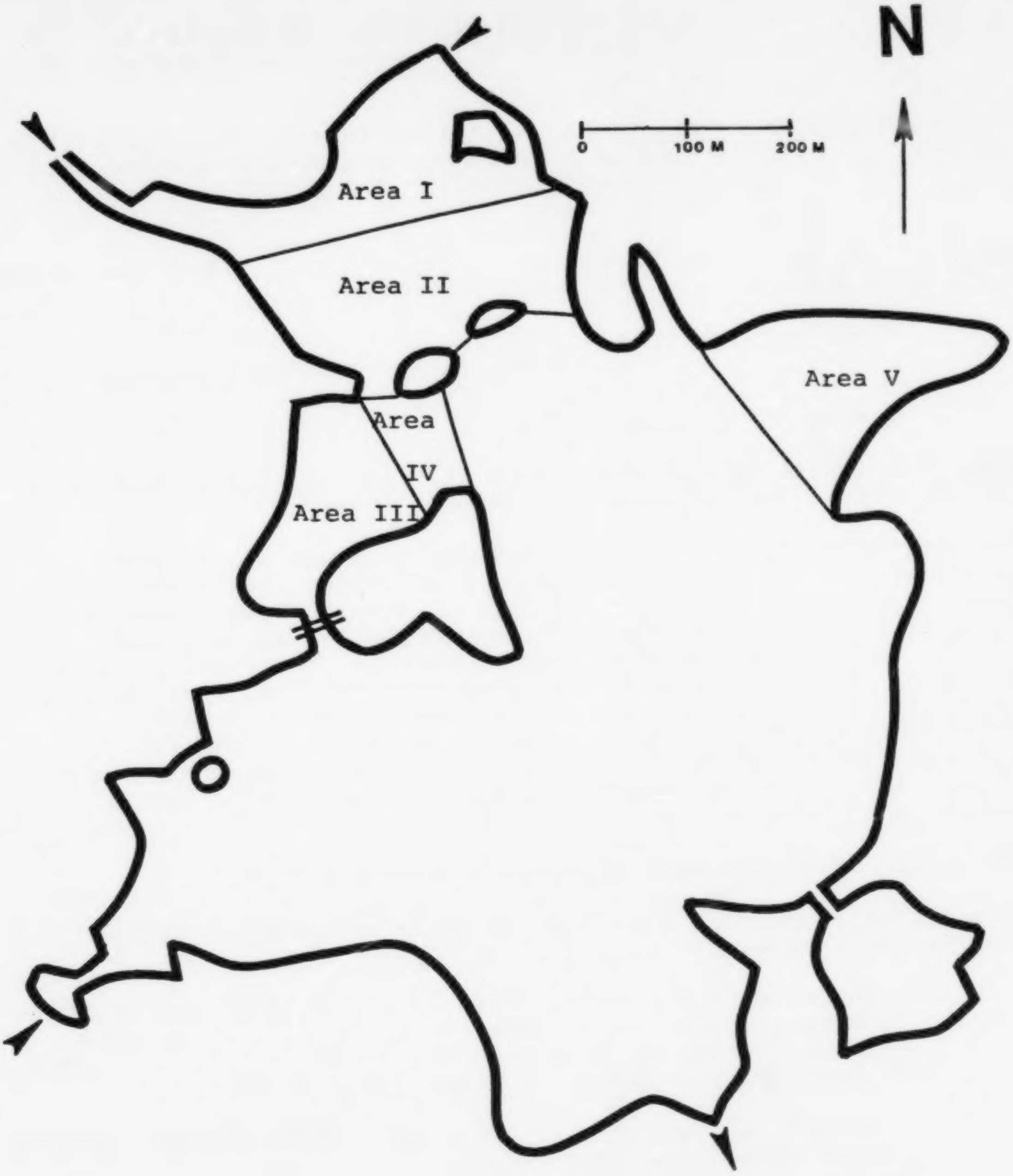
N
0
100 M
200 M
Area I
Area II
Area
IV
Area III
Area V

Figure 8. Dredging Areas as Proposed at Project Initiation.

releases but add to program costs and slow the dredging when only one dewatering lagoon is used. Two main lagoon areas would result in faster dredging as compared to use of a sand filter.

5- Dredging close to shore is disliked by dredge operators because of tree roots, generally thinner layers of organic sediment, and the difficulty of constantly changing the height of the cutterhead.

6- The process of getting all the approvals and permits for dredging and preparation of bid specifications will take one to two years.

7- It is critical for a town to assign someone full-time to any dredging program.

8- Dredging in the summer generally stimulates phytoplankton growth (See Table 2.), via nutrient releases from the organic sediments as documented in Appendix D.

9- Dredging in an isolated part of the lake has less influence on phytoplankton than dredging in the main body of the lake. (See Table 2.)

10- During dredging,white water lily and spatterdock rhizomes and clumps of arrow arum will drift around the lake and will require extra personnel time for control.

11- Submerged plants will be cut loose by the dredge and will drift away from the dredging site. Control measures should be considered. These could include floating booms for containment.

12- Complete removal of organic sediments is impossible and a thin layer of organic and inorganic sediments will end up in undredged areas nearest the dredging operation.

13- Spatterdock seedlings were observed in dredged areas while white water lily seedings were not observed in the 1979 aquatic plant survey.

Program Summary

The eight tasks defined above constituted the lake restoration program. However, of these tasks, two tasks clearly dominate this restoration program; i.e., Task 7, Chemical Management, and Task 8, Dredging. These two tasks will be discussed in greater detail in later sections of the report after the lake, its hydrology and nutrient loading have been discussed in more detail.

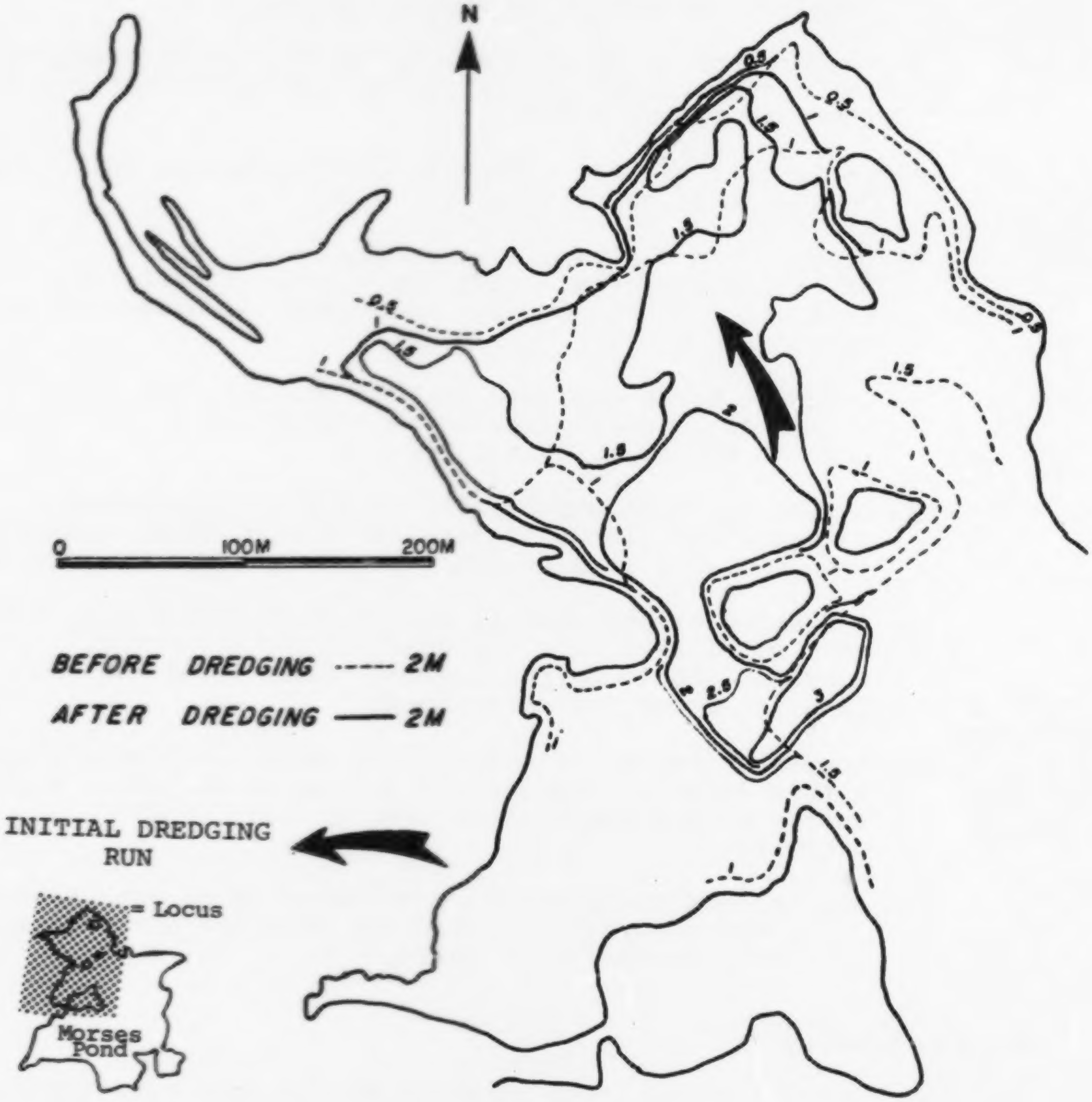
N
0
100M
200M
BEFORE DREDGING ---- 2M
AFTER DREDGING —— 2M
INITIAL DREDGING RUN
= Locus
Morses Pond
0.5
1
1.5
2
2.5
3

Figure 9. Water Depth Contours in Meters Before and After Dredging.

4.0 WATER AND NUTRIENT BUDGETS

Some of the general statistics for Morses Pond have been presented in Table 1. However, these simple statistics cannot do justice to the complexity of any lake system. Thus this section of the report will focus on lake systems in general and will then focus specifically on Morses Pond.

The present state-of-the-art in modeling a lake's response to a nutrient loading is based on input-output models. The models in widest use today were developed by Vollenweider (1968; 1975; 1976). Since Morses Pond is nitrogen limited and since Vollenweider's 1976 model does not deal with nitrogen, the 1975 model will be used throughout this report. Note that this is the latest nitrogen load model. All models developed since have dealt exclusively with phosphorus.

It is also recommended that Vollenweider's 1975 phosphorus model be used for small lakes rather than the 1976 model. The 1976 model assumes no internal nutrient loadings and assumes phosphorus sedimentation is proportional to phosphorus concentration in the water. In the case of small lakes the plant growth may induce significant phosphorus recycling and may actually control the phosphorus retention. In addition, in deep eutrophic lakes, hypolimnetic phosphorus recycling can be significant. For these reasons, it is recommended that the 1975 model be used along with measured phosphorus retention, measured hypolimnetic loading and estimated loading from aquatic plant communities.

In dealing with environmental models it is always critical to note the limits of the models. For example, one stated limit for all lake models is:

> "It is not technically valid to utilize a loading diagram based on phosphorus loads when the key limiting element is nitrogen."
>
> Rast and Lee (1978) p. 370

The reason for the lack of technical validity is not obvious until one considers the character of nutrient behavior in lakes relative to the input-output model. In the case of the non-limiting nutrient what occurs is:

1- the non-limiting nutrient remains in excess in the water and thus the outflow load becomes much larger than the outflow load would be if the nutrient were limiting; and

2- when this high outflow load is subtracted from the inflow load, the resulting input minus output value incorrectly predicts the lake's trophic status as being too low relative to the trophic curves.

In terms of a reclamation program, the impact of dealing with the non-limiting nutrient may cause serious economic penalties. For example, if the impact of the non-limiting nutrient were reduced, the main effect would be to lower output of the non-limiting nutrient with only a small impact on the trophic status of the lake. Only when the non-limiting nutrient has been reduced to such a large extent that, in fact, it would become the limiting nutrient; then, and only then, would a dollar invested in reducing the nutrient load yield a full dollar's worth of benefits. While the nutrient is non-limiting, there will be less benefit per dollar spent. For this reason nitrogen management of nitrogen limited lakes may be far more cost-effective than phosphorus management of nitrogen limited lakes.

This brings us to another issue, the issue of when to identify the limiting nutrient.

> "It is not the limiting nutrient over the annual cycle that is of importance in determining what nutrient should be considered in remedial treatment of the nutrient loading to a water body. Rather, the growing season is the period of primary concern, since algal growth during the non-growing season is seldom of consequence in terms of eutrophication control in natural waters."
>
> Rast and Lee, 1978, p. 49

The two quotes presented above clearly imply that selecting a phosphorus management scheme for a lake restoration program without careful identification of the limiting nutrient could result in a less cost-effective program or even failure of a lake restoration program. For these reasons, this program, demonstrating that nitrogen control of lakes is technically feasible, fills a critical void in applied lake management.

4.1 The Limiting Nutrient in Morses Pond

The identification of limiting nutrient can be achieved two ways via nutrient testing in lake waters. The first method involves repeated testing until biologically available nitrogen or biologically available phosphorus goes to zero in the lake system. Unfortunately, this might not occur in any given lake in any given year. Fortunately, nitrogen ÷ phosphorus (N/P by weight) ratios can also be used.

In the case of Morses Pond identification of the limiting nutrient was made in 1973 and 1974. Allen (1973) concluded that the lack of nitrate-nitrogen in the late summer of 1973, while ortho-phosphate was still detectable in the water, was an indication that nitrogen was probably the limiting factor. Thompson (1975), in presenting the results of the 1974 survey, showed that in June, prior to the lake's first alum treatment, the total nitrogen/total phosphorus ratio integrated from three stations in the main body of the lake was less than 2.1, clearly indicating nitrogen limitation. Thompson's data is reproduced in Table 5.

TABLE 5 - Morses Pond Nutrient Data Before First Alum Treatment, June 26, 1974.

	Total P	TKN	NO_3-N	N/P	Composite N/P
Sample 1	0.33	1.05	0.60	5.0	2.07
Sample 2	1.80	1.05	0.62	0.9	
Sample 3	0.13	0.75	0.63	10.6	

Further confirmation of the nitrogen limited status comes from algal growth work at Wellesley College. Lake Waban is almost immediately downstream from Morses Pond and it has no major tributaries except for the Morses Pond outlet. Water samples taken from Lake Waban were used for algal growth media. Dr. Mary Allen (personal communication) said that numerous attempts to culture algae in Lake Waban water were unsuccessful unless nitrate was added to the growth media. This confirms the nitrogen limited status of these lake systems.

4.2 Water Budget

A nutrient budget cannot be any more accurate than the underlying water budget. Thus an accurate water budget is fundamental to an accurate selection and evaluation of a lake reclamation program. For New England, Knox and Nordensen (undated) supply data for average annual precipitation, runoff, and lake evaporation. These represent the basic hydrologic input into an average annual water budget. However, marrying these average annual flows to associated water quality data is no simple matter.

The problem of developing flow and water quality interrelationships may be summarized as follows:

1- Base flow (dry weather flow) water quality is different from storm water quality because storm waters have significantly higher nutrient concentrations.

2- Base flow quality may or may not have large seasonal variations.

3- Sampling for base flow quality may be affected by rainfall that occurred within the previous 24 hours.

4- Storm flow sampling from urbanized areas is affected by time since the last rainstorm.

5- To properly quantify storm flow quality, the amount of base flow and its quality must be known prior to the storm so that actual quantity and quality of storm water runoff can be calculated.

6- Storm water quality varies with rainfall intensity and/or total amount of rainfall.

7- Storm water quality varies with rainfall variations within the storm.

Given all these complexites, it is required to move carefully to begin to understand the total problem. While this project cannot begin to fully explore all these flow and water quality interrelationships, this project has made some contribution towards resolving these issues.

The first issue to be covered is the quantification of the base flow portion of the annual runoff into the lake. For this study, a U.S.G.S. gaging station at a small drainage basin was evaluated. The station selected was Boulder Brook gaging station at East Bolton, Mass. The drainage area was 3.99 km (1.54 mi) and there was no major ponding area that would alter the storm flows from this small basin. The daily flows (U.S.G.S. 1974-1978) were plotted for five hydrologic years and best professional judgement was exercised to draw a curve on each annual hydrograph to separate base flows from storm flows. The result was that 83% of the total flow was base flow. While this value may seem high, it must be remembered that while base flows are low, they extend over the entire year, even when storm flows are added to them. The 83% can be compared to 67% base flow for the gaging station at Ipswich, Mass. (Sammel et al. 1966). The gaging station at Ipswich has a lower percentage base flow because the drainage basin has about 25% wetlands which lower the base flow by enhanced evapotranspiration.

The monthly distribution of base flow averaged for the five year evaluation period is presented graphically in Figure 10 and in numerical form in Table 6. The remaining 17% of flow is storm flow.

Table 6. Average Monthly Distribution of Base Flow and Precipitation.

Month	% Annual Base Flow	% Annual Precipitation Worcester Airport *
Oct.	2.8	7.8
Nov.	8.0	9.1
Dec.	12.7	7.8
Jan.	11.5	8.4
Feb.	13.4	6.6
Mar.	20.2	9.3
Apr.	16.6	8.7
May	8.8	8.5
Jun.	3.8	8.3
Jul.	1.2	8.0
Aug.	0.5	9.0
Sept.	0.5	8.5
Totals	100.0	100.0

* Lautzenheiser (1969)

In terms of using the East Bolton, Mass. gaging station for identifying base flow values, the following comments apply.

1- The basin is the smallest basin available for analysis in eastern Massachusetts and this small size makes it easy to resolve base flow versus storm flow conditions.

2- The geology of the drainage basin is totally igneous just as is the Morses Pond drainage basin.

3- Use of the rural Bolton area for determining base flows is an acceptable starting point for Morses Pond providing some correction is made for the urbanized portion of the Morses Pond drainage basin. Such a correction has been made for this study as defined later in this section.

Evaluation of the storm flows and their associated nutrient loading requires an advance in the state-of-the-art. The approach used for this project was to analyze rainfall data so that we could understand the flow portion of the relationship. For evaluation purposes, the U.S. Department of Commerce (1966-1976) hourly rainfall records at Worcester, Massachusetts Airport were used. These data were evaluated to determine the number of rainfall events per year relative to the "time between flushings" for urbanized areas. Sartor and Boyd (1972) demonstrated that solids loading per curb mile was related to the time since last rainfall. Since flushing of streets is a major component of storm loading in ubanized areas, and since nutrient accumulation is related to input-output on impervious and pervious surfaces, it was deemed necessary to correct nutrient loading for this time since last flushing. The original data from Sartor and Boyd (page 208) were re-evaluated and it was decided that after five days of no rain, nutrient loading per curb mile generally stabilizes. Given a stability in nutrient loading after 5 days, it was decided that storm loading measurements after 5 days of no rain would give a valid picture of a generally balanced land flushing condition. Given more complete data, it may be that nutrient loading beyond the five day period does increase, but right now the five day period is assumed valid.

Given this background, the hourly rainfall data for Worcester was evaluated as a function of time since last flushing. The results of this rainfall analysis plus the rainfall-runoff studies of Fabuss et al. (1972), who analyzed the Boston data, lead to the following conclusions.

1- Fabuss et al. (1972) concluded that 0.0076 mm of rainfall (0.03 inches) over a three hour period is not enough to produce runoff.

2- There are 65 rainfall events each year, February to November inclusive, in eastern Massachusetts capable of producing runoff, i.e., larger than the runoff limit as defined in the statement above.

3- The number of rainfall events each year decreases with increasing time between runoff events.

4- The average amount of rainfall for the first day of each storm increases with increasing time between runoff events.

5- The estimated amount of rainfall which occurs in storms too small to produce runoff is 2.14% of the total rainfall.

6- 4.3% of the total rainfall is lost to runoff via storage and evaporation before runoff begins in larger storms. The 4.3% figure is derived from the initial 0.0076 mm of rainfall required to wet the ground and fill small storage sites before runoff can occur.

While these statistics and conclusions may not seem to be important in a lake study, they do have a significant impact on estimation of the storm loading portion of the nutrient budget. The summary statistics from the Worcester Airport rainfall data are presented in Table 7.

As a final note on water budgets, there should be a way to correct the overall water budget of a lake for increased evapotranspiration when there is a large wetland associated with the lake. Based on data presented in Hutchinson (1975), and Bernatowicz (1976), it is estimated that evapotranspiration from wetlands is double expected lake evaporation. In addition, it is well known that urbanization increases storm flow and decreases base flow. It is further assumed that storm flow volumes are doubled by urbanization. Both of these assumptions need research in order to refine the overall water budget calculation process.

4.3 Nutrient Budget

The nutrient budget for Morses Pond is derived from the water budget as related to inflow and outflow quality. In the case of Morses Pond, the focus is on the nitrogen budget due to the nitrogen limited nature of the system.

For the base flow portion of the nitrogen budget, the evaluation is relatively straightforward. The base flows are calculated for each of the four sub-basins, distributed by month and then multiplied by expected average nutrient concentration as observed from 1975 to 1978.

TABLE 7. SUMMARY RAINFALL STATISTICS FROM THE WORCESTER AIRPORT

(The data were taken from 1966 to 1976, February to November, inclusive.)

Time in Days Between Rainfall Large Enough to Produce Runoff	Number of Events	Average Amount of Rainfall 1st Day of Storm in Inches	Percent of 1st Flush Rain
1	144	0.4725	19.3
2	107	0.5022	15.3
3	90	0.5792	15.0
4	67	0.7215 *	14.0
5 or more	201	0.628	36.4
			100 %

---

* This value was biased upwards by some very large storms of several days duration. When only storms of short duration are used, the upward trend is continuous.

Unfortunately, the storm flow portion of the nutrient budget is much more complex. In the case of storm flows we are faced with the fact that research is still underway in this area, Bedient (1978), and the few storms that were actually monitored during this program can only point towards the solution and not give it precise definition at this time.

There are several methods of evaluating storm water quality. One method is to simply assume that the average concentration observed in the various storms can be applied to the total storm runoff volume. However, in light of recent work, this appears to be greatly over-simplified and thus is an inaccurate estimation for storm loading. Bedient et al. (1978) have shown that there a is linear relationship between nutrient loading and total runoff volume. While the four storms that were monitored at Boulder Brook did not include a rainfall event over 10 mm (0.4 inch), the data suggest that this type relationship is valid for the Morses Pond watershed. Thus, a complete statistical analysis was made for rainfall intensity versus storm loading. Rainfall intensity was used instead of runoff volume because storm intensity is expected to have good correlation with total runoff volume. The results of this first step in the analysis yields a total nutrient load assuming that each storm has had 5 days to allow the land to build up a stable load. Correcting for the amount of runoff that occurs with less than 5 days between storms results in a 20% reduction of the total expected nutrient load.

The final results of all this analysis is that the expected nutrient loading from storm runoff can be expressed as a unit weight of nutrient per unit area of drainage basin per year. The result for nitrogen is 3,250 gm/ha/yr and, for phosphorus, 650 gm/ha/yr. Added to this, one must include the nutrient loading for rainfalls in excess of 24 hour duration. Here, given the limited data available, an average nutrient concentration is applied. This may over-simplify the nature of the real world, but it is reasonable given lack of detailed definition of nutrient loading for longer duration storms. What is needed for clarification of this issue is continuous sampling for storms of two to three days duration.

The final external source for Morses Pond is atmospheric loading. Uttormark et al. (1974) have mapped nitrate and ammonia nitrogen values for rain for the United States. The value from this map was used for atmospheric loading. Dry fall and leaf loading are excluded from the external nutrient budget.

For outflow of nutrients, the water budget was calculated for each month using the following assumptions.

1- Base flow is distributed by month as shown in Table 6.

2- Storm flow and direct precipitation is equally distributed by month with zero storm flow used for cold months. Cold months as defined here are half of December and March and all of January and February. The equal distribution assumption is justified by the even distribution of monthly rainfall (See Table 6).

3- Evaporation is distributed by month according to field data recorded by Rohwer (1931).

4- Water taken from the lake by nearby town wells takes dissolved nutrients with it. Wellesley draws 2.1 MGD all year while Natick draws 0.75 MGD in the summer.

5- Base flow plus storm flow plus precipitation minus evaporation equals outflow volume.

6- Groundwater contributions in this man made lake is assumed to be negligible, Winter (1976).

The result of these assumptions completes the general nutrient budget as shown in Table 8. In terms of external sources, 40% of the nitrogen input is retained in the lake. The nutrient budget as calculated is shown on the Vollenweider curves in Figure 10. Note that even with blocking nitrogen fixation as an internal nutrient source, the lake is still eutrophic given its present external loading of nitrogen.

A word of caution. The 40% retention figure is not a real retention value. In small shallow lakes, such as Morses Pond, there is internal nutrient recycling from decay of macrophytes in the winter and from metabolism by-product release in the summer. If these inputs could be accurately defined for complex plant communities and their total interaction with organic sediments, then and only then, could a true retention value be calculated. The winter portion of this internal budget has been calculated as a minimum of 250 kilograms nitrogen for 11.2 hectares of the lake that are known as recycling areas. This value was calculated from the increase in winter nutrient concentrations in an isolated cove over that of the open lake waters. However, since there is some flushing of this cove in the winter, the 250 kg represents only the known excess nutrient storage in the water column. The amount lost to the main body of the lake in winter could be many times the observed storage.

Notice also that all internal nutrient recycling regardless if from macrophytes, or from nitrogen fixing blue-green algae, will move the lake's nutrient status further into the eutrophic classification as shown on Figure 11.

TABLE 8. SUMMARY NUTRIENT BUDGET

	Vol. in ha-m	N Load in kg	Average Concentration
Base Flow †			
Boulder Brook	122.6	2,301.5	1.88
Bogle Brook	461.5	6,638.3	1.44
Jennings Brook	195.3	3,104.0	1.59
Adjacent Land	96.4	1,804.1	1.88 *
Subtotal	875.8	13,847.9	
Storm Loading			
Flushing Events of Duration 24 hrs or Less	247.1	7,199.4	2.91
Runoff for Following Days of Longer Duration Storms	29.0	493.0	1.7
Subtotal	276.1	7,692.4	
Atmospheric Loading	47.2	82.3	0.17
TOTAL INFLOW		21,622.6	
Outflow	1,169.2	12,850.5	1.10
Inflow minus Outflow		8,772.1	

† Monthly nutrient concentrations for inflows and outflows can be derived from data in Appendix B.

* Assumed the same as Boulder Brook because other streams have upstream ponds as nutrient sinks.

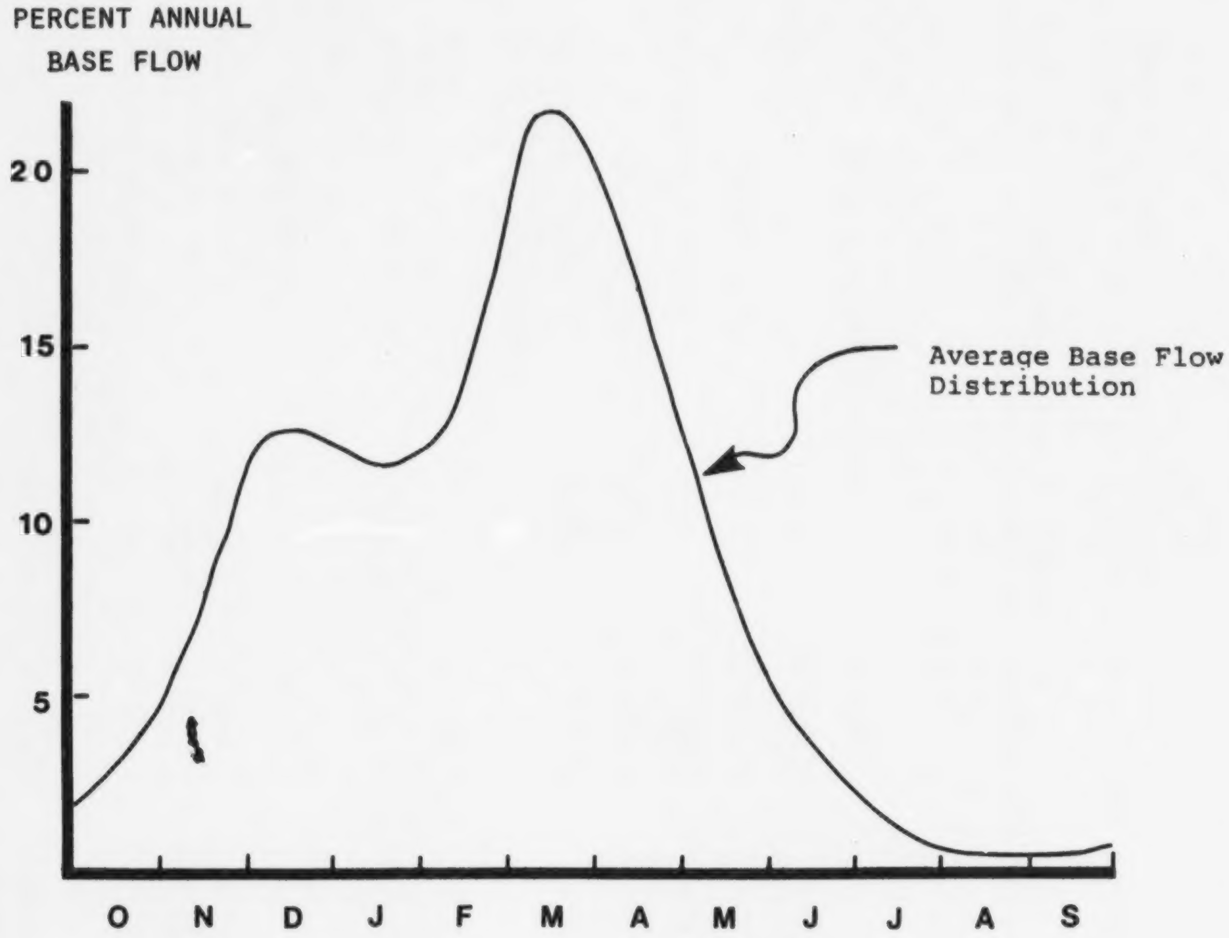

Figure 10. Annual Distribution of Base Flow

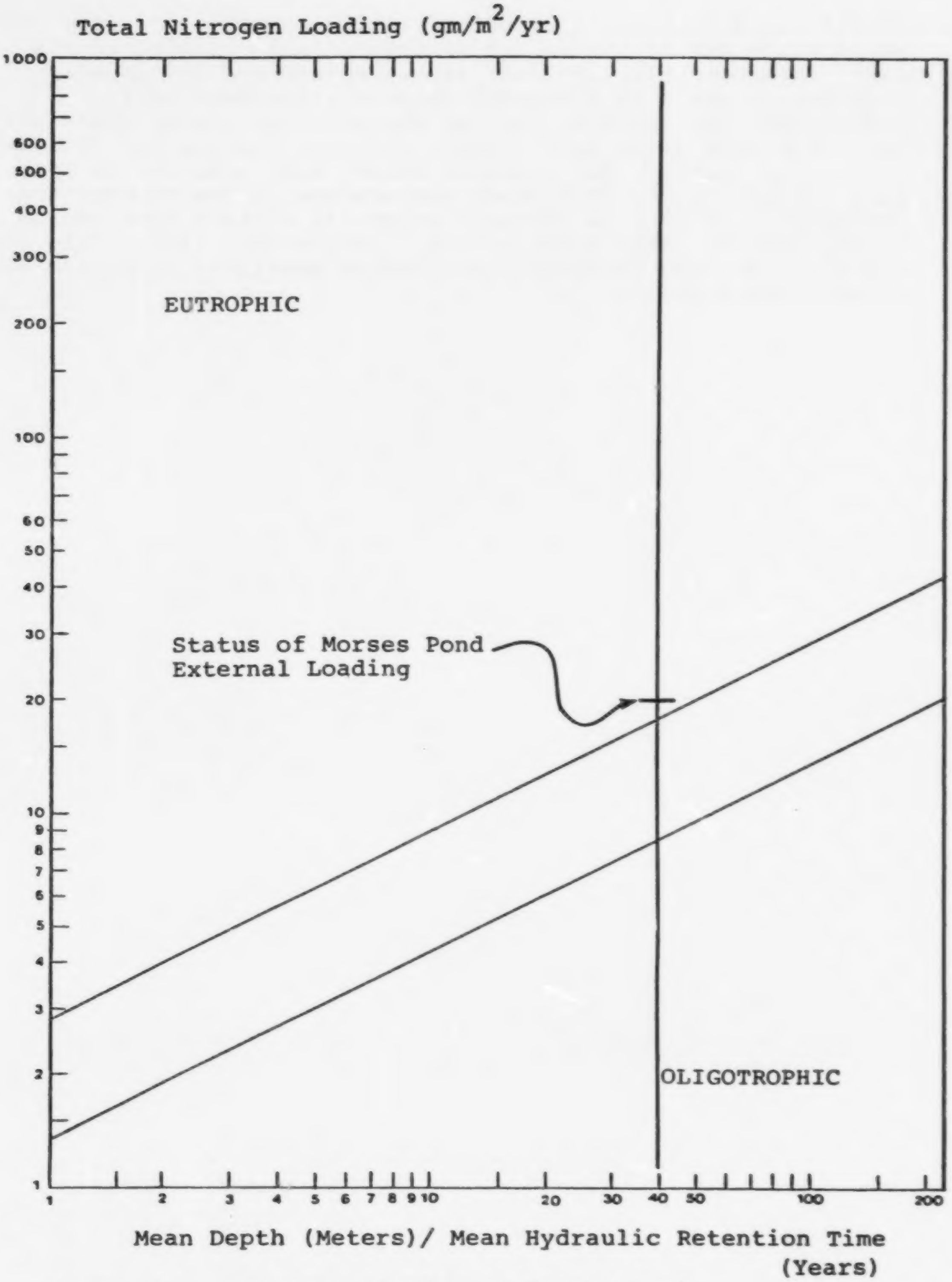

Figure 11. Nutrient Loading of Morses Pond

It was hoped that the limited chemical data available from 1974 would allow definition of the nitrogen fixing loading in the lake. Unfortunately, the data is too sparse and too erratic relative to the post treatment data to allow meaningful evaluation. For example, just as the nitrogen fixing algae show up on the 1974 algal data sheets, chemical testing for nitrogen in the lake ceased. One possible reason this occurred is that the firm conducting the 1974 study was mislead by the concept that "phosphorus control is the only essential element that can be easily made to limit algal growth." (Golterman, 1975). This seems plausible because phosphorus monitoring continued after the bloom of blue-green algae.

5.0 CHEMISTRY AND CHEMICAL TREATMENT

Having summarized the lake's nutrient budget, there are some general chemical considerations that should be discussed in more detail. Thus, the goals of this section are to define the lake's chemical character in more detail and to define the lake's response to the chemical treatment and dredging portions of the program.

5.1 Direct Chemical Internal Nutrient Recycling

Internal nutrient sources are obviously related to both chemistry and biology of the lake. However, for discussion purposes here, hypolimnetic nutrient release from sediments will be considered as chemical recycling even though the driving mechanisms are largely biological in origin.

Concerning hypolimnetic nutrient recycling, the area and volume potentially involved are less than 5% and less than 1% respectively (See Figures 1 and 3). In 1975, hypolimnion formation was confined below depths ranging from 4.8 m (16 ft) to 5.4 m (18 ft). In 1974, two vertical profiles were made in the lake, one in March and the other in July. In March the only total phosphorus value recorded at depth was 0.17 mg/l while surface values averaged 0.03 mg/l. Total nitrogen at depth was 6.69 mg/l while surface values averaged 5.68 mg/l. Notice that the recycled N/P ratio is 7.2. These nutrient increases document winter hypolimnetic release. The July sampling event occurred after the initial alum (without $KMnO_4$) treatment and phosphorus values at depth did not show any summer nutrient recycling. Nitrogen observations were not taken.

In 1975, after the second alum treatment (with $KMnO_4$), the hypolimnion was sampled for four weeks in the summer. The average surface concentrations of N and P were 0.543 mg/l and 0.042 mg/l respectively, while hypolimnetic values of samples taken one foot from the bottom were 0.904 mg/l and 0.077 mg/l respectively. The results show a N/P ratio for released nutrients of 10.5. Notice that the N/P ratio of 10.5 is almost exactly equal to the average N/P ratio of 10.4 by weight of typical phytoplankton as reported by the Federal Water Pollution Control Administration (1968). Thus, the summer hypolimnetic nutrient increase is probably from decay of algal cells sinking from the surface rather than release from the sediments below. Because no summer hypolimnetic nutrient recycling occurs, and since the volume of the hypolimnion is so small, there has not been any hypolimnetic nutrient sampling since 1975 nor were any summer vertical profiles made in 1976, 1978, or 1979.

The only other work done on hypolimnetic and direct chemical releases by organic sediment was to sample pH, Eh and DO to catch the extremes of a 24 hour cycle to see if pH-Eh cycles could stimulate nutrient release from the sediments. A calm day was selected to minimize effects of currents. Sampling began at noon and was completed at 6 AM the next morning.

The temperature data showed only minor variations. The pH was stable in both the epilimnion and hypolimnion of the open lake station. However, the pH in the two weed infested areas did show some variation. pH was highest in the late afternoon and early hours of darkness. The range in pH was 6.7 to 8.0.

DO was quite stable in the epilimnion of the open water station, and had a general downward trend in hypolimnion. Hypolimnetic DO values had a high of 3.4 mg/l at noon and a low of 0.8 mg/l at 4 AM. The 6 AM value was 1.8 mg/l suggesting that substantial DO improvement occurred with the first rays of the sun stimulating phytoplankton activity. DO in the weed infested areas showed a maximum at 5 PM with lows at 4 AM. Values ranged from 8 to 12 mg/l at both stations.

Eh was the most variable parameter. Eh varied widely in the afternoon and may reflect the patchiness of flow regimes at all stations. Eh was generally stable after 10 PM with all stations showing a general drop in Eh values at 4 AM with a sharp recovery by 6 AM. The pH-Eh values all fall in the normal range for natural aqueous environments as diagrammed by Board (1977).

The variations in Eh and pH were plotted on the iron solubility diagram of Hem (1970). This indicated that daily hypolimnetic variations are not responsible for iron release from hypolimnetic sediments. The other stations all indicated the daily pH-Eh cycles in the water would have the potential to stimulate nutrient release from shallow sediments by changing the iron solubility. Given that macrophytes stimulate pH changes, the total nutrient release potential of weed infested lakes will be the sum of both direct release of metabolism by-products by the plants as well as induced nutrient release from the sediments by changes in pH and Eh. This is an area where more research is clearly needed. The pH, Eh, DO and temperature data are reproduced in Table 9.

5.2 Biological Nutrient Recycling

Since plants leak fluids into surrounding water, it is important to know what the character of these fluids is in order to determine the nature of the impact on lakes. The two plants investigated in this project were spatterdock (Nuphar variegatum Engelm.) and water lily (Nyphaea odorata Ait.). Fluids were extracted from the mature plants by squeezing the plants in a

TABLE 9. pH, Eh, DO DATA, AUGUST 12, 1977

Three sampling stations were chosen, and represented four possible conditions during the 24-hour cycle. Station H, an open lake site, was sampled at the surface and at the bottom to compare epilimnetic and hypolimnetic states. Stations I and Q are highly productive areas with dense vegetation growths. Station H can be compared to both Stations Q and I in order to ascertain differences between relatively unproductive areas (H), and highly productive areas (I and Q). Station Q is located in a sheltered area, and so the waters are circulated less than at Station I. The 18 hours of actual sampling were sufficient to monitor the extremes in the 24 hour cycle. Note that patchiness in water parameters is seen in the hypolimnion.

Station I

Time	1200	1400	1540	1720	1920	2030	0005	0337	0505
Temp (°C)	30.0	28.3	28.0	28.2	27.0	26.5	26.3	26.2	26.0
pH	7.1	7.1	6.8	7.8	7.5	7.1	7.1	7.0	6.7
Eh	95	100	74	72	75	95	90	52	99
D.O.	8	10	10	12	11	11	10	9	9

Station Q

Time	1200	1425	1550	1730	1930	2037	0015	0350	0520
Temp(°C)	28.0	28.0	28.0	27.3	27.0	26.9	26.3	26.3	26.0
pH	7.5	7.1	6.9	7.58	7.8	8.0	7.2	6.79	6.7
Eh	90	90	60	100	80	78	80	72	95
D.O.	9	10	11	12	11	12	10	8	9

Station H-hypolimnion

Time	1200	1440	1600	1750	1945	2052	0030	0400	0535
Temp(°C)	21.7	22.0	21.0	24.0	21.0	21.0	20.5	19.8	21.0
pH	6.2	6.1	6.2	6.29	6.2	6.45	6.2	6.17	6.1
Eh	30	120	30	70	120	105	110	51	88
D.O.	3.4	2.0	2.6	1.8	1.8	2.0	1.6	0.8	1.8

Station H-epilimnion

Time	1200	1440	1600	1750	1945	2052	0030	0400	0535
Temp(°C)	27.5	28.0	29.0	28.5	27.5	27.5	27.0	26.6	27.0
pH	6.7	7.1	7.2	7.4	7.2	7.45	6.8	7.30	7.0
Eh	65	100	90	100	90	83	90	32	90
D.O.	9	9	10	9.5	9	9	9	9	9

Eh in millivolts
D.O. in mg/l
pH as $-\log_{10} [H^+]$
Maximum air temperature 25.5°C
Minimum air temperature 17.8°C

press and by grinding the plants and then filtering to obtain plant fluids.

The results of this testing (Table 10) indicated the following.

1- The spatterdock released a purple fluid from the stems that smelled like freshly crushed grapes. The source of the grape smell was not determined.

2- The spatterdock easily yielded its fluids by squeezing the stems while water lilies would only release a few drops of fluid at the force limit of the hand operated press.

3- Grinding of spatterdock produced a fluid with a greater concentration of nutrients than did the squeezing process.

4- All fluids from plants subject to only one picking had a total N/P ratio (by weight) averaging 5.4 with a range of 2.14 to 9.10. For biologically available forms, the N/P ratios averaged 2.9 with a range of 0.74 to 9.0.

5- For one area of spatterdock which was picked once in June and again in August, the first picking so altered the plant cluster that the total N/P ratio shifted to 21.1 while the biologically available forms approximated the original N/P ratio.

Besides nutrient release from these floating leaf plants, there is nutrient release from emergent and submerged plants. None of these latter plant types were evaluated in this study. However, Schroder (1975) did study nutrient release during the growing season from stands of emergent plants dominated by the reed Phragmites communis. The observed nutrient releases were 4.4 mg P/m^2 and 8.0 mg mineral nitrogen ($NH_4+NO_3+NO_2-N$) per square meter. If the fluids released from the emergent plants are chemically proportional to the fluids released by the floating leaved plants, the total N/P ratio will equal 7.3. The importance of this ratio will become evident in a later section.

5.3 Cation Relationships to Algal Blooms

Shannon (1970) used Pearsall's Cation Ratio as a predictor of algal bloom potential in Florida. Pearsall's Cation Ratio is $(Na+K)\div(Ca+Mg)$. While Pearsall's Cation Ratio may be a valid predictor of algal bloom potential in other parts of the world, in New England it is meaningless due to the variable impact of highway salting on the sodium content of lakes. In an attempt to develop a cation predictor for use in New England, numerous

TABLE 10. NUTRIENT CONTENT OF PLANT FLUIDS - Spatterdock (Nuphar variegatum Engelm.) and the White Water Lily (Nymphaea odorata Ait.)

Date	20Jun78	20Jun78	20Jun78	20Jun78	20Jun78	9Aug78	9Aug78
Species	s'dock	s'dock	s'dock	white	white	s'dock	s'dock
Location	A	A	B	A	B	A*	B
Treatment	squeeze †	grind §	grind	grind	grind	squeeze	squeeze
Total phosphorus (mg/l)	12.0	82	203	90	105	2.3	15.8
Ortho-phosphate (mg/l)	3	75	180	75	30	2.3	14.8
Total Kjeldahl nitrogen(mg/l)	94	150	653	746	386	46	77
Ammonia nitrogen (mg/l)	22	30	53	56	56	17.3	16.8
Nitrate nitrogen (mg/l)	∿5	∿25	∿30	∿75	∿75	∿2.5	∿3.0
Nitrite nitrogen (mg/l)	0.5	0.6	<0.05	<0.05	<0.05	<0.05	<0.05
Iron (mg/l)	6.2	15.0	78	87	164	8.6	15.4
Total Alkalinity (mg/l as $CaCO_3$)	79.6	905	4,776	1,323	1,423	21.9	41.3
Magnesium (mg/l)	43	134	110	144	150	20	31
Sodium (mg/l)	135	512	587	1,150	1,050	83	208
Calcium (mg/l)	80	105	240	168	178	73	87
Potassium (mg/l)	550	1,875	1,450	975	912	250	510
Aluminum (mg/l)	9.8	27	26	126	110	6.2	3.6

* Spatterdock were collected from the same stand on 20 June and 9 August. The heavy picking may have produced stress conditions on the plants.

† Stems of the plants were squeezed in a press to obtain intracellular fluid.

§ Stems and leaves of the plants were ground and filtered to obtain the resulting liquid.

A=Natick portion of Morses Pond (see Figure 5).

B=Proposed dredging area I and II (see Figure 8).

analyses were attempted. The only analysis that resulted in a clear separation of lakes with algal blooms from lakes without algal blooms resulted from setting the value for sodium at 5 mg/l. Five was selected because Ward (1974) showed in laboratory tests that values in excess of 5 mg/l do not further stimulate blue-green algal blooms. Using a real sodium value in excess of 5 masks the micronutrient-algal growth relationship.

Using the value of 5 for sodium, the modified Pearsall's Cation Ratio can be plotted against the lake's trophic status as evaluated on the trophic curves of Vollenweider (1975). Since the lakes in the study group are both nitrogen limited and phosphorus limited, comparison can only be made on an artificial scale related to the Vollenweider curves. This artificial scale has been developed by setting the distance from the oligotrophic-mesotropic boundary to the mesotropic-eutrophic boundary as one trophic unit. Scaling of similar parallel units then creates a new scale that may be applied to any lake: regardless if nitrogen or phosphorus is limiting; regardless of the actual load of the limiting nutrient; and regardless of the mean depth - mean hydraulic retention time. This new scale is shown in Figure 12. Given any trophic position on either Vollenweider diagram, a dimensionless trophic value can be assigned. Figure 13 shows the modified Pearsall's Cation Ratio plotted versus the new trophic scale.

As further data becomes available for New England lakes, it may be necessary to revise this curve. At this time, it serves as a working tool for limnologists until further refinements are made. Table 11 is the Figure 13 lake list.

TABLE 11. Lake Listing for Figure 13.

A= Laurel Lake
B= Stockbridge Bowl
C= Pontoosuc Lake
D= Lake Richmond
E= Lake Buel
F= Onota Lake
G= Rosemary Lake
H= Pillings Pond
I= Lake Quannapowitt
J= Lake Garfield
K= Lake Shirley
L= Plunkett Reservoir
M= Ashmere Lake
N= Goose Pond
O= Morses Pond

5.4 Chemical Response to Chemical Treatment

For $KMnO_4$ treatments, the lake was divided into seven segments and each segment was dosed separately using the 10 minute jar test, Carus Chemical Company (1972). The Carus Chemical Company (1973) recommends that doses in excess of 3 mg/l not be used. If the demand is greater than 3 mg/l, it is recommended that the

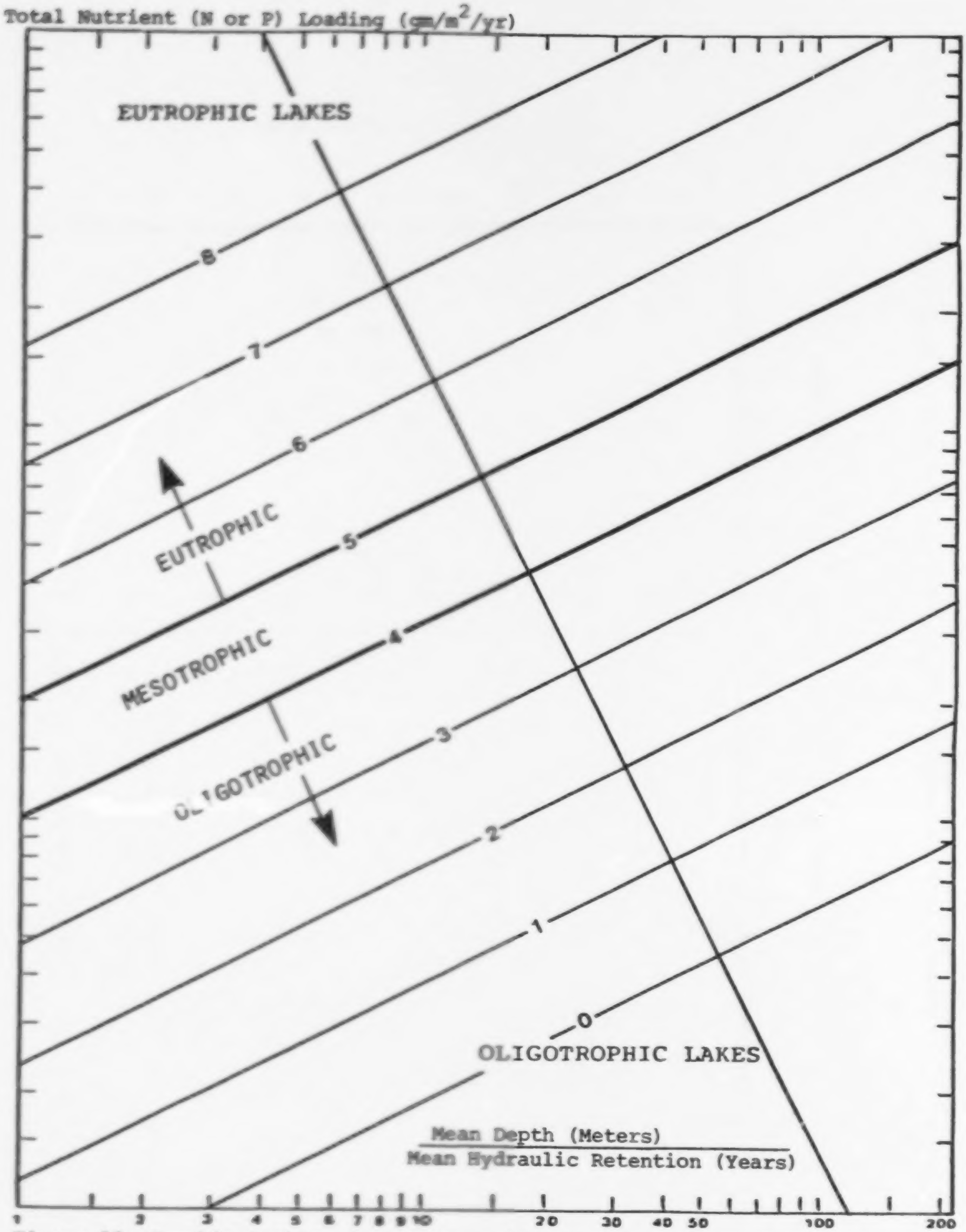

Figure 12. Trophic Scaling from Vollenweider Curves. Diagonal Units are trophic scaling using upper and lower mesotrophic boundaries of Vollenweider (1975) as one trophic unit.

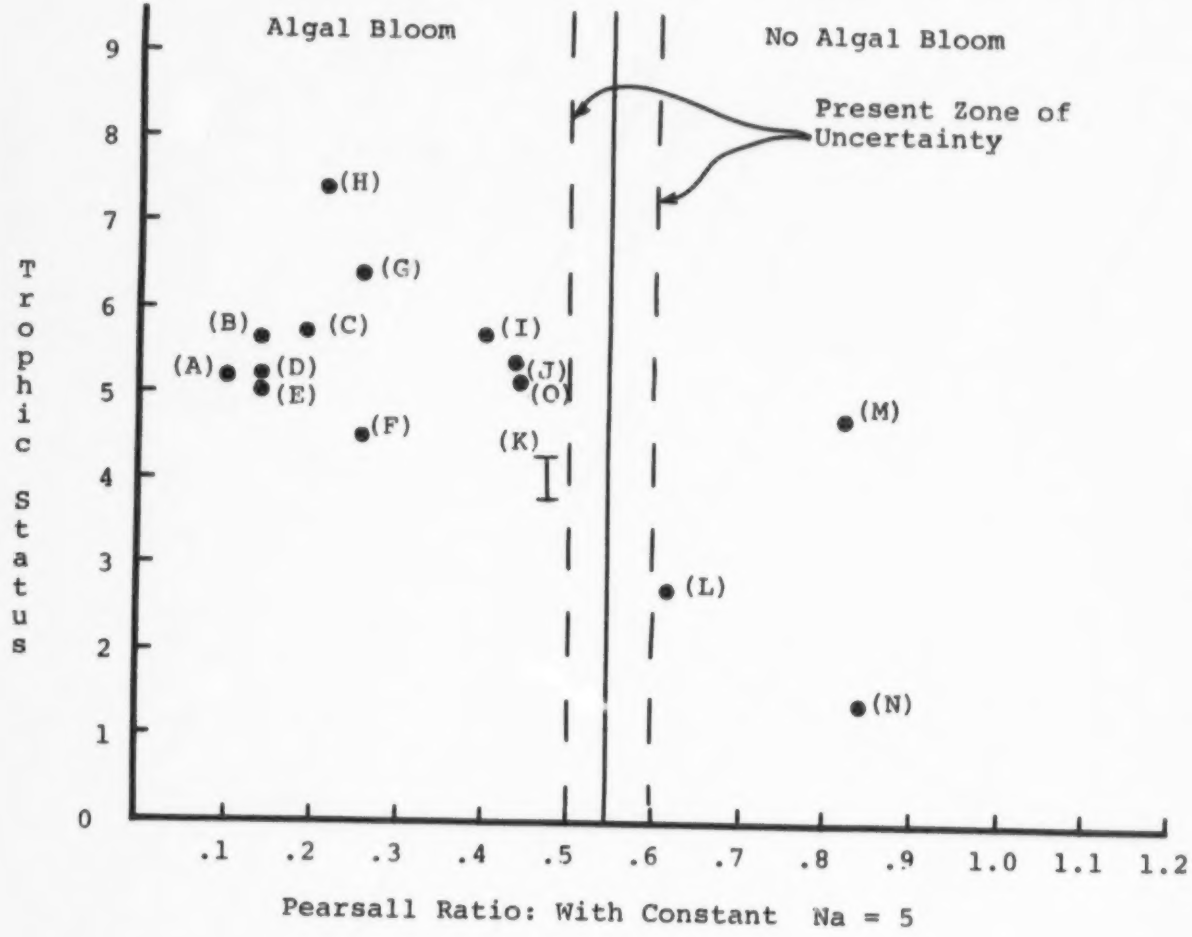

Figure 13. Modified Pearsal's Cation Ratio versus Trophic Status

entire lake be treated at 3 mg/l and then return in a day or two to give the final application.

Morses Pond is divided into 7 segments, 6 surface areas plus the hypolimnion. Figure 14 shows the surface areas and the hypolimnetic area is determined from Figures 1 and 3. Segments 4, 5, and 6 were well mixed and homogeneous and required the same general doses (See Figures 14 and 2). Segments 1, 2, and 3; with their extensive stands of aquatic plants; required much higher doses due to the organic complexes and associated higher iron concentrations in the water. The hypolimnion also had a higher demand for $KMnO_4$ due to decay products from organic debris on the lake bottom.

In 1975, the first year $KMnO_4$ was tried in Morses Pond, some tank tests were conducted on pond water. Ten gallon aquaria were filled with raw Morses Pond water, complete with an extensive zooplankton population. The water was aerated during the test period. Doses of 2 mg/l were used, which were greater than the demand for $KMnO_4$. The water in the test tanks remained pink for over a week and the zooplankton in the tanks remained viable and active during the entire week. Thus dilute $KMnO_4$ overdoses apparently present no problem to the zooplankton community. Actual dose rates applied to Morses Pond are presented in Table 12.

Table 12. Dose Rates for Morses Pond, 1975 - 1979. $KMnO_4$

Segment	1975	1976	1977	1978*	1979**
1	1.0	1.7	1.5	2.0	2.0
2	1.4	2.2	1.8	1.9	2.4
3	1.5	1.3	1.3	1.7	1.7
4	1.2	1.1	1.3	1.5	1.7
5	1.2	1.1	1.3	1.6	1.7
6	1.2	1.1	1.2	1.5	1.6
7	3.0	1.1	1.5	1.8	2.6
Weighted Mean	1.34	1.15	1.32	1.66	1.89

* Hard Winter, thick ice.
**Dredging prior to treatment.

The method of application of $KMnO_4$ used by the Wellesley Department of Public Works is as follows. The town purchased a workboat and a mixer used by fire departments for making fire fighting foam. An intake hose runs over the side of the boat to the mixer. The free-flowing grade of $KMnO_4$ is poured into the mixer and the crystal-water mixture is discharged via plastic pipes into the wake of the boat. It is important to use the free-flowing grade of $KMnO_4$ because the other grades may cake and this greatly slows the operation. Morses Pond treatment typically takes a full day because of the need to determine the stratification and the dose required for the deep layer before $KMnO_4$ application can begin in the surface areas.

It must be stressed that $KMnO_4$ imposes strict handling and storage requirements. Anyone proposing to use this material should phone the Carus Chemical Company to discuss protective procedures and to acquire their safety material (1974). A cleansing solution should always be kept on hand when $KMnO_4$ is used. A solution of half hydrogen peroxide and half clear vinegar was recommended by a staff member of the Carus Chemical Company. This solution has been used to clear the skin stains that result from use of $KMnO_4$. On two occasions this solution was used for items more severe than stains. In one case, a worker got some $KMnO_4$ dust in his nasal passages. He sniffed the solution directly up his nose to stop the burning. In another case, a worker removed his goggles and accumulated $KMnO_4$ dust around the edge of the goggles blew into his eyes. A few drops of the solution into each eye stopped the burning and left only the smarting of the vinegar. These were the only two problems in the five years of handling $KMnO_4$.

Of the greatest concern in this program is the impact of the use of $KMnO_4$ in open waters. To determine this impact, testing was done on the day of $KMnO_4$ treatment and again on the day following treatment in the years 1976, 1978, and 1979. The chemical effects observed were the expected conversion of iron to insoluble form plus an unexpected overnight loss of nitrogen in the lake system. This loss was 19% in 1976, 42% in 1978, and 39% in 1979; for an average loss of 33%. The nitrogen component lost varied from year to year. Cause of the loss is not known, but it is suspected that the loss may be as gas bubbles containing NO_2 and/or NH_3. Table 13 presents the before and after data.

No effort has been made to quantify DO immediately before and after treatment. However, since $KMnO_4$ is known for relief of oxygen deficiency in fish ponds, an increase in DO is clearly expected. With respect to DO changes, it should be noted that both the epilimnion and hypolimnion of the pond are treated with $KMnO_4$. Thus, hypolimnetic DO increases should temporarily inhibit any nutrient release from sediments in the deepest parts of the lake. It would be interesting to know if $KMnO_4$, at the 10 minute demand doses used, oxidizes any of the surficial layer of the organic sediments. For example, while the 24 hour cycle pH-Eh variations could stimulate iron release from sediments (See Table 9), it could also very well be that these cycles were much larger in years prior to use of $KMnO_4$. Further research is needed in this aspect of sediment-water interactions.

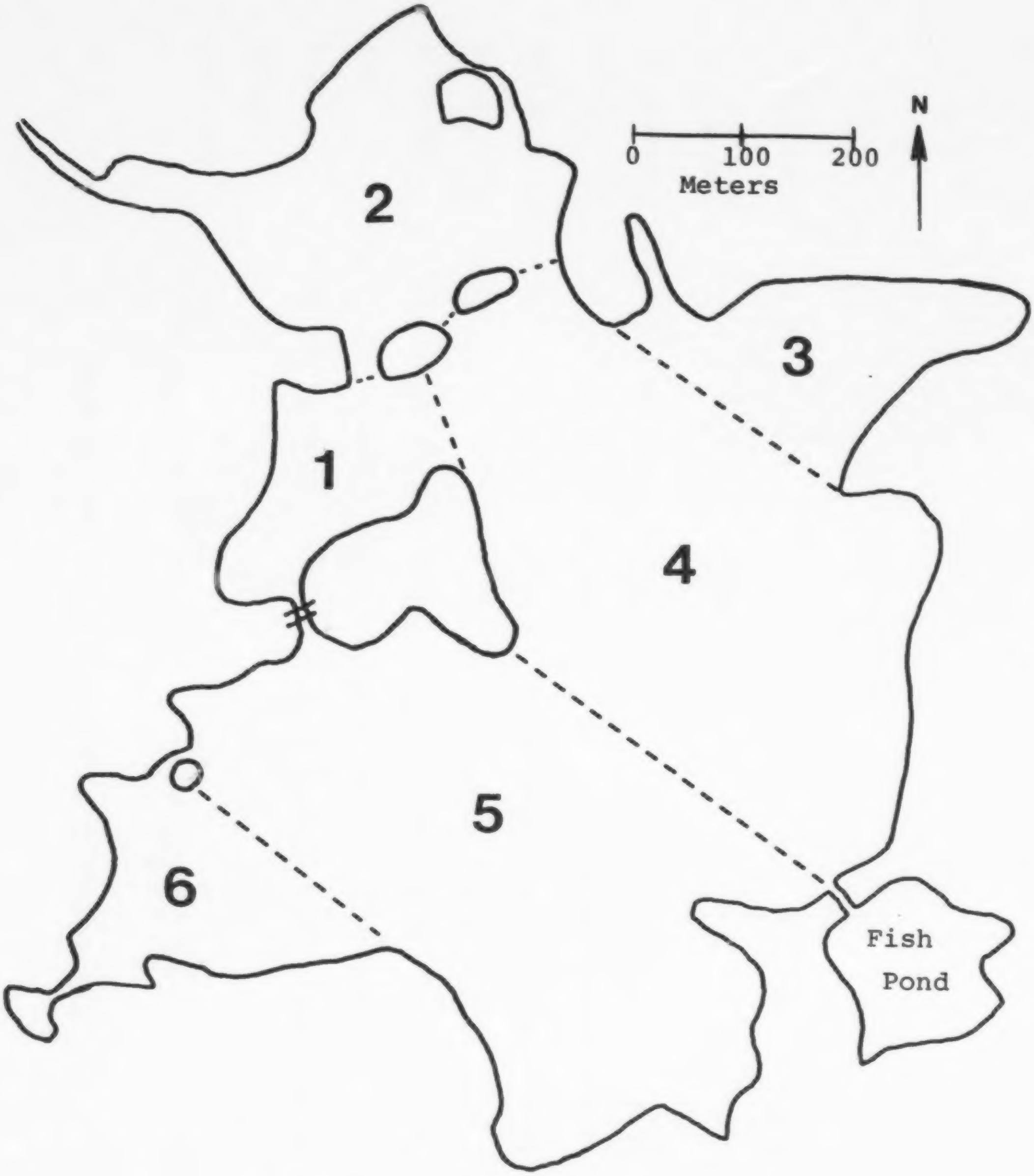
N
0
100
200
Meters
1
2
3
4
5
6
Fish
Pond

Figure 14. Lake Segments for Potassium Permanganate Treatments. Segment 7 is the hypolimnion. The fish pond area was not treated.

TABLE 13. Pre- and Post- $KMnO_4$ Treatment Chemical Data.

	1976				1978				1979			
Treatment	Pre		Post		Pre		Post		Pre		Post	
Sample	1	2	1	2	1	2	1	2	1	2	1	2
P-t	<0.01	<0.01	0.02	<0.01	0.03	0.03	0.04	0.05	0.08	0.05	0.06	0.03
P-O	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.01	0.01	0.01	<0.01	<0.01	<0.01
Kj-N(TKN)	0.32	0.43	0.38	0.36	0.70	1.20	1.00	0.15	1.60	1.40	0.80	0.75
NH_3-N	0.13	0.16	0.13	0.10	0.35	0.25	0.05	0.05	0.30	0.50	0.25	0.35
NO_3-N	0.65	0.52	0.35	0.45	0.21	0.40	0.12	0.20	0.25	0.30	0.30	0.30
NO_2-N	0.005	<0.005	0.006	<0.005	0.01	0.01	<0.005	<0.005	0.01	0.01	0.02	0.02
Fe (Ferric)	0.06	0.01	0.16	0.15	-	-	-	-	0.35	0.36	0.38	0.35
Fe (Ferrous & Organic)	0.07	0.08	<0.02	<0.02	-	-	-	-	-	-	<0.02	<0.02
Alkalinity	-	-	-	-	-	-	-	-	23.4	26.5	28.4	26.7

Besides the immediate loss of nitrogen due to $KMnO_4$ treatment, the dissolved iron and iron found in organic complexes is converted to insoluble iron oxides or hydroxides by the oxidizing action of $KMnO_4$. These insoluble particles tend to agglomerate, flocculate and settle and thus are slowly removed from the system. In 1975, even with alum treatment, iron flocculation in Morses Pond continued to lower the total iron concentration for over 9 weeks in the main body of the lake.

To test for adequacy of iron removal (defined here as conversion to insoluble forms that are not available to the biological system rather than actual physical removal from the water), the results of $KMnO_4$ treatment have constantly been to lower values of soluble iron to less than 0.02 mg/l in Morses Pond on the day after treatment (See Table 13).

There are no known or suspected long term or short term problems with use of $KMnO_4$ in open lake water as long as the dose does not exceed the 10 minute demand. There are no problems because the active ingredient is oxygen and iron and manganese by-products are innocuous.

As part of the chemical treatment program, alum has been used to rapidly clear the water of suspended manganese dioxide resulting from the $KMnO_4$ applications. The application of alum for Morses Pond has always been as a commercial alum slurry. Three tanker truck loads are required to produce an averge dose of 35 mg/l. In the early years, this dose was applied evenly to the pond. In later years, the applications were concentrated in the deepest portions of the lake to prevent alum floc build up in shallow areas. It takes a full day to place each tanker load into the lake. The Wellesley Department of Public Works uses the same workboat for alum as for $KMnO_4$. The $KMnO_4$ mixer is replaced with a 250 gallon tank centered in the workboat. The tank is filled from shore and a portable pump is used to drain the the tank into the wake of the boat.

In 1977, 1978, and 1979, alum floc became resuspended due to a windy period following the alum application. In some circumstances, as in 1979 when the floc particles were large, this floc settled out by itself. However, in 1977 and 1978, the suspended particles were quite small and were not settling out. Thus one extra tanker load of alum was applied and all the alum settled out.

Besides the effects of $KMnO_4$, there are some possible effects from the use of alum in this program. For example, one effect of 5 years use of alum in Morses Pond is the build-up of several centimeters of alum floc over most of the deepest area of the pond. In addition, alum floc may have been incorporated into the sediments in shallow areas. No investigation of the alum floc has been made on the benthic invertebrates.

This accumulation of alum floc on the pond bottom and its possible resuspension is the only known or suspected long term problem with alum use. The alum applied from the period 1974 to 1979 will have a fine layer of sediment over it due to the action of the dredge. This could help keep the alum floc down. However, if alum use continues into the future, the potential for a major resuspension of the floc increases. Possible solutions to this long term problem could include (1) small scale suction cleaning of the pond bottom in the deep areas, (2) resuspension of the floc in the Spring during high flow periods to flush the floc from the pond or (3) alum use could be discontinued in the pond. If alum use were discontiued in Morses Pond, the management program would have to be altered. The major alteration would be that $KMnO_4$ treatments would have to be done some 6 to 8 weeks prior to opening the beach to public recreation. This would allow for some, and hopefully most, of the residual MnO_2 to settle out. This could result in somewhat lower visibilities in the pond, but swimming would clearly continue. $CuSO_4$ treatments would have to be very timely and deal with pre-bloom conditions to prevent visibility losses.

It may also be possible to switch from alum to some other coagulation aid, such as Ca^{++}, a polyelectrolyte or pH control could be substituted for alum. Posselt et al. (1968) discusses some of the issues associated with removal of suspended MnO_2.

Based on the potential for long term problems with alum, it is specifically recommended that management of Morses Pond be attempted without alum use. With proper timing, this technique has the potential to maintain swimming while eliminating the need for expensive alum treatments.

In addition, the application of alum to the open waters of the lake could also increase the chances of the lake becoming temporarily phosphorus limited via nutrient stripping of the water or permanantly phosphorus limited via inhibition of internal nutrient recyling of phosphorus. Based on the data available, the N/P ratios hint that the lake's limiting nutrient may be changing. These ratios imply:

1973 - nitrogen limited - Allen (1973);

1974 - nitrogen limited - Thompson (1975);

1975 - nitrogen limited - six sampling dates, two stations;

1976 - undetermined - insufficient data;

1977 - nitrogen limited - 4 sampling dates;

1978 - undetermined - 4 sampling dates: 2 samples showed phosphorus limitation, and 2 samples showed nitrogen limitation; and

1979 - undetermined - insufficent data. One July sampling date showed possible phosphorus limitation.

In 1978 and 1979, the nutrient ratio data show the first indications of phosphorus limitation. This may be due to the alum treatments.

However, before jumping to the conclusion that alum treatments alone are responsible for the apparent phosphorus limitation, it should be pointed out that the sewering programs in Natick and, immediately around the pond in Wellesley, may have had an even larger impact than the alum treatments.

The expected impacts of this sewering activity is clearly important. For example, the N/P ratio for septic tank effluent averages 3.8 (Tyler et al. 1978). This means that elimination of septic tanks and cesspools near a lake would reduce phosphorus loading more than nitrogen loading; thus, driving the lake towards phosphorus limitation. This will especially be true for older homes where the phosphorus adsorption capacity of the soils may be totally used and all the nutrients leaving the septic tanks eventually reached the lake.

5.5 Chemical Response to Dredging

One of the goals of this program was to examine the response of the lake to on-going dredging. Unfortunately, there were not enough funds to monitor the entire chemical response of the lake to dredging. Instead, some monitoring near the dredge during actual operations was conducted. Sampling was conducted in the plume if dredge and control samples were taken from two areas not affected by the dredging plume (See Appendix D). In this case, suspended particles in the water altered the values of total nitrogen and total phosphorus. Thus the focus here has to be on biologically available forms of these nutrients. There was no increase in ortho-phosphate in the dredging plume. This is to be expected because dredging in shallow water with a large cutterhead tends to oxygenate the water, thus inhibiting phosphorus release.

However, all forms of biologically available nitrogen were released by dredging. Nitrite-nitrogen was slightly increased, nitrate-nitrogen almost doubled and ammonia-nitrogen was increased by several hundred percent. The impact of all this nitrogen release during a sustained period of dredging was to satisfy the nitrogen demand in the system, thus driving the lake towards a phosphorus limited condition during dredging. This largely explains the N/P ratio of 44.5 observed on July 26, 1979. Dredging began in April and was ongoing through this sampling date.

5.6 Water Chemistry, Bedrock, and Wetlands Relationships

The bedrock in this drainage basin is all non-carbonate igneous and metamorphic rocks and the three major streams feeding the lake each have variable amounts of wetlands in their drainage basins. Thus the only comparison that can be made for geology, wetlands and water quality is to compare the data from this site to water quality data from Berkshire County Massachusetts where similar geology, wetlands, and water quality relationships are known.

Table 14 presents data taken in the summer of 1976 in Berkshire County. These data show that carbonate versus non-carbonate bedrock geology does have an impact on the nitrogen concentration in the water in the case where there are no significant wetlands in the drainage basin. When wetlands are present, this difference is effectively eliminated. For phosphorus, the carbonate versus non-carbonate geology is not significant. However, wetlands do have considerable impact on phosphorus. Where major wetlands do occur, summer base flow phosphorus concentrations are higher than when wetlands are absent. For carbonate bedrock areas, the wetlands present produce a greater nitrogen concentration in the water than for drainage basins lacking significant wetlands. Unfortunately, the data cannot be tied into flows or integrated into storm data to fully develop a picture on the impact of wetlands and geology on total nutrient budgets.

In the case of Morses Pond, there are complicating factors that prevent generalizations from being made with respect to wetlands. These complicating factors include urbanization, which greatly affects runoff quality, and existing ponds just above two of the three sampling stations. This latter factor means that the ponds as nutrient sinks or sources may have masked the character of the impact of the wetlands. The data for Morses Pond tributaries are presented in Table 15. Again, it is the lack of daily flow data in each sub-basin that prevents integration of flow and quality data so that the real impact of wetlands can be determined. If flows are not significantly reduced by wetlands, the increased nutrient concentrations mean increased loading on lakes. If flows are reduced proportionately to increased nutrient concentration, then there will be no difference between runoff loading from uplands and wetlands. If flows are reduced in excess of nutrient enhancement, then wetlands are not sinks for nutrients. It should be pointed out that this would apply to the base flow portion of the hydrologic cycle and evaluation of the storm runoff portion

TABLE 14. SUMMER BASE FLOW QUALITY, BERKSHIRE COUNTY

	Undeveloped Areas No Wetlands (# of observations) mg/l	Undeveloped Areas With Wetlands (# of observations) mg/l
Non-Carbonate Areas		
Nitrogen	0.489 (15)	0.401 (4)
Phosphorus	0.018 (11)	0.025 (2)
Carbonate Areas		
Nitrogen	0.254 (19)	0.412 (11)
Phosphorus	0.017 (24)	0.024 (17)

TABLE 15. BASE FLOW QUALITY OF MORSES POND TRIBUTARIES

	Yearly P Concentration mg/l	Summer N Concentration mg/l	Yearly N Concentration mg/l	Percent Wetlands
Tributary				
Boulder Brook	0.125	1.4	1.87	7.5 %
Bogle Brook*	0.103	0.9	1.44	19 %
Jennings Brook*	0.157	0.8	1.59	40 %

* Pond just above sampling station.

of the cycle would be required to complete the picture of wetland impacts on nutrients. These are all areas needing further research.

5.7 Seasonal Variations of Water Quality

In terms of base flows, seasonal variations of nutrient concentrations are important in terms of planning any monitoring program. For phosphorus, the data fail to demonstrate any significant seasonal variation. This conclusion is supported by Taylor et al. (1971), reporting on nutrients in streams in Ohio. What can be noticed in the Morses Pond data is a variation in phosphorus concentration from year to year. Again, only by integration with flow data can it be determined if:

- concentration varies but annual loading remains constant;
- concentration variations affect annual loading in a linear fashion; or
- variation in concentration and flow cause wide variations in annual phosphorus loading.

The yearly variations observed in phosphorus concentrations suggest that three or four years of phosphorus monitoring may be necessary to develop an accurate picture of the base flow portion of the average annual phosphorus loading. One year of monitoring does not address the complications introduced by yearly changes in base flow quality.

Iron behaves in an interesting fashion. In the years when the iron concentration is high, the phosphorus values are low and vice-versa. This suggests that in the presence of iron, phosphorus (1) interacts with the iron to form insoluble iron phosphate compounds, or (2) adsorbs on the surfaces of insoluble iron hydroxide particles. Regardless of the actual mechanism, the general inverse correlation of iron with phosphorus suggests that phosphorus is lost in stream systems when iron levels are elevated. Like phosphorus, iron shows no significant seasonal variation but there are apparent variations from year to year in average concentration.

As for nitrogen, there does not appear to be any correlation with phosphorus or iron. What is seen is a seasonal variation. The seasonal variation in total nitrogen shows a gradual rise in concentration beginning in November or December, peak values occurring in January or February, and then dropping to a low but relatively constant level for the rest of the year. In Boulder Brook, the brook with no pond and about 10% wetlands, there is an April minimum which is quite pronounced. This suggests that groundwater phosphorus consumption by vegetation is quite active at the start of the growing season. The wetlands and ponds may mask this phenomenon in the other tributaries.

5.8 Storm Water Quality

In considering the nutrient loading from the streams tributary to Morses Pond it was obvious from the general literature that storm flow quantification was going to be a complex problem. Thus, some monitoring effort was aimed at evaluation of this key issue. Since sampling is critical in understanding storm loading, the procedure will be discussed prior to the data review.

The storm sampling procedure utilized in this study invloved:

1- a sampling of base flow quality several hours prior to the initiation of runoff;

2- composite sampling over short time periods yielding 5 to 7 samples per storm for storms of short duration;

3- numerous recordings of rainfall and stream height; and

4- calibration with current meters for flow versus stream height to accurately quantify flow volumes.

As an example, at a given station, one-third of a gallon of water would be taken every 10 minutes until a gallon of water was collected. Water height and raingage readings were made in between samples. This gives a detailed picture of stream response to a rainfall event.

This procedure allows accurate determination of the storm loading because base flows and associated concentrations can be numerically removed from the results. This is clearly a required procedure for any storm sampling program where base flows pre-exist at the sampling location. Failure to correct for base flows can yield significant errors in determining storm flow nutrient loadings and may so alter statistics that rainfall-runoff land use relationships are masked. Once base flows and associated nutrient loads are separated from actual field results then the data begins to reveal the real character of storm runoff quality.

For illustrative purposes, two storm events as monitored at Boulder Brook will be reviewed. The first storm occurred on 14 March, 1978. The rainfall was 6.9 mm (0.27 inches) with runoff occurring as a single peak flow in a simple hydrograph. A small amount of snowmelt was contributing to base flow. The combined base flow and storm flow showed simultaneous peaks with nutrient concentrations as shown in Figure 15. When base flow is subtracted from combined loads, the results clearly show the heaviest nutrient concentration at the start of the storm indicating a first flush phenomenon for phosphorus, nitrogen and iron as shown in Figure 16.

The second storm selected for discussion began on October 1, 1978. This storm involved 6.0 mm (0.235 in.) of rainfall producing two peaks of flow. In this case, the nutrient behavior was quite variable. Nitrogen showed a single peak while phosphorus and iron showed peaks matching the flow curves (Figure 7). When base flows and associated nutrients are subtracted from the combined flows, it is seen (Figure 18) that:

1- phosphorus concentrations remain generally constant with a small decrease in concentration during the second flow peak, representing dilution;

2- nitrogen shows a peak coinciding with the first rainfall peak but decreased during the second peak, indicating an initial first flush followed by dilution; and

3- iron showed a double peak generally coinciding with flow peaks.

Notice in this latter storm that nutrient concentrations are generally enhanced on the day following the storm. This is why it is recommended that sampling for base flow not be done on the day after a rainstorm. Such near-storm samples could bias the nutrient evaluation when a single number is applied to a month of flow. Note further that nutrient concentrations vary greatly depending on the character of the storm. This is why grab samples during storms are not representative of the total storm or of average storm runoff.

These two storms of similiar amounts of rainfall produced widely different nutrient loadings in terms of grams per hectare of drainage basin. The two other storms monitored for Boulder Brook closely match the 14 March storm in intensity and nutrient loading in gm/ha. This leads to the tentative conclusion that rainfall intensity may be a variable that allows prediction of nutrient loading. More research will be needed to confirm this conclusion and to see what the character of the predictor is in large intense storms. No other data except the nutrients and associated flows were monitored in the storm sampling.

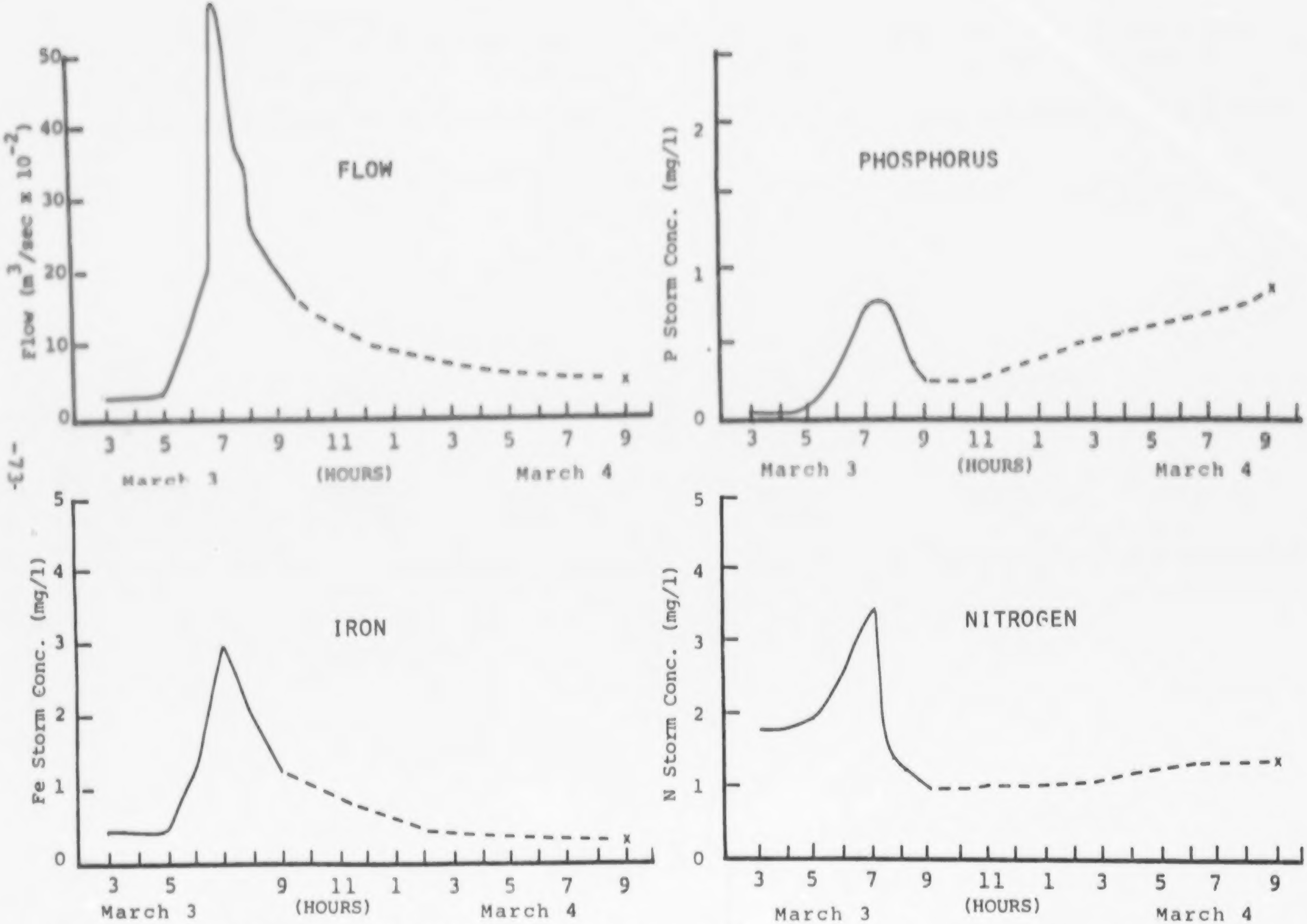

Figure 15. Boulder Brook Field Results, Storm of 3 March 1978. All values represent combined storm flow and base flow. Dashed lines represent interpolation between last two samples.

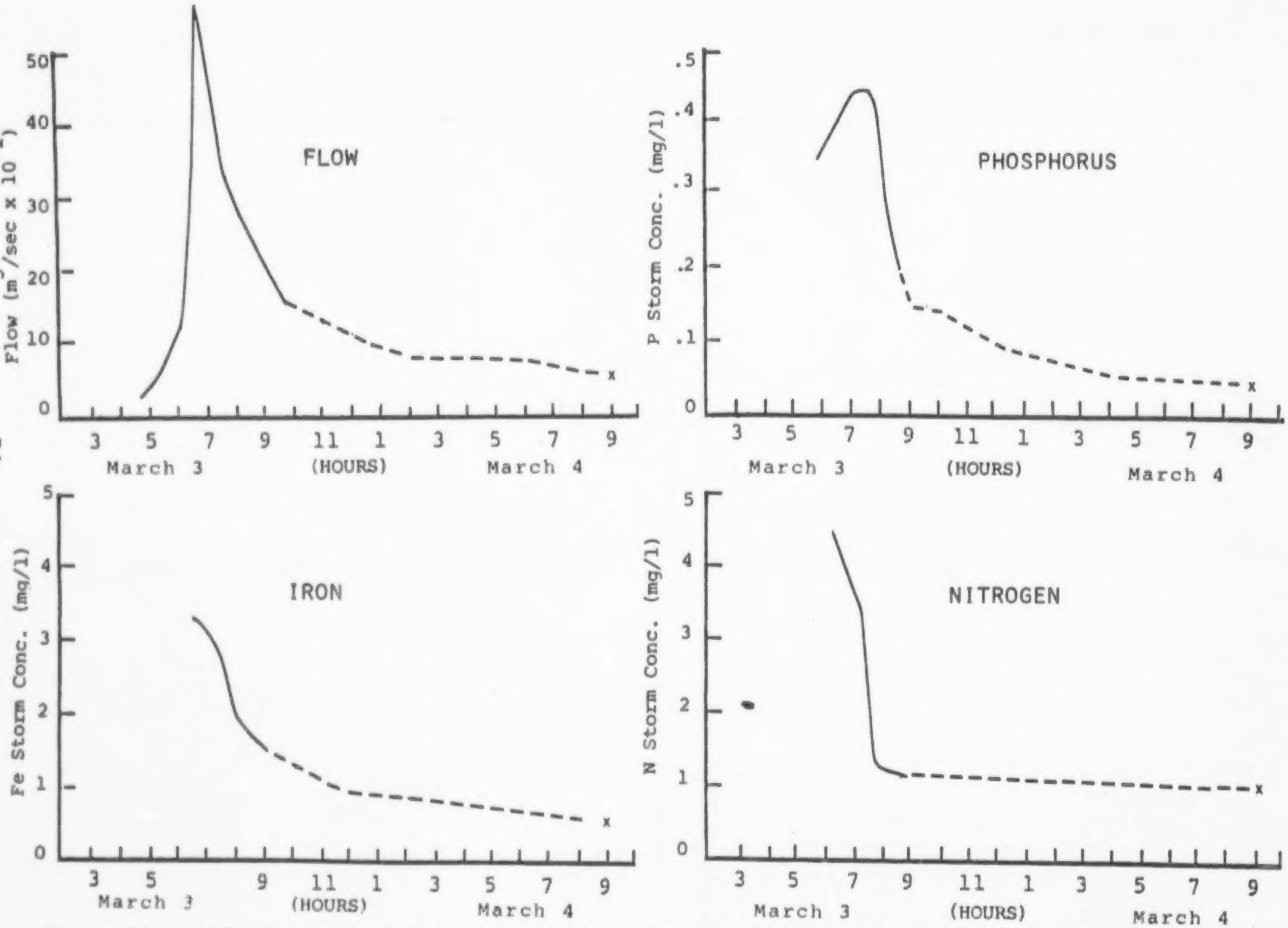

Figure 16. Boulder Brook Storm Data Corrected by Removing Base Flow, 3 March 1978. Dashed lines represent interpolation between last two samples.

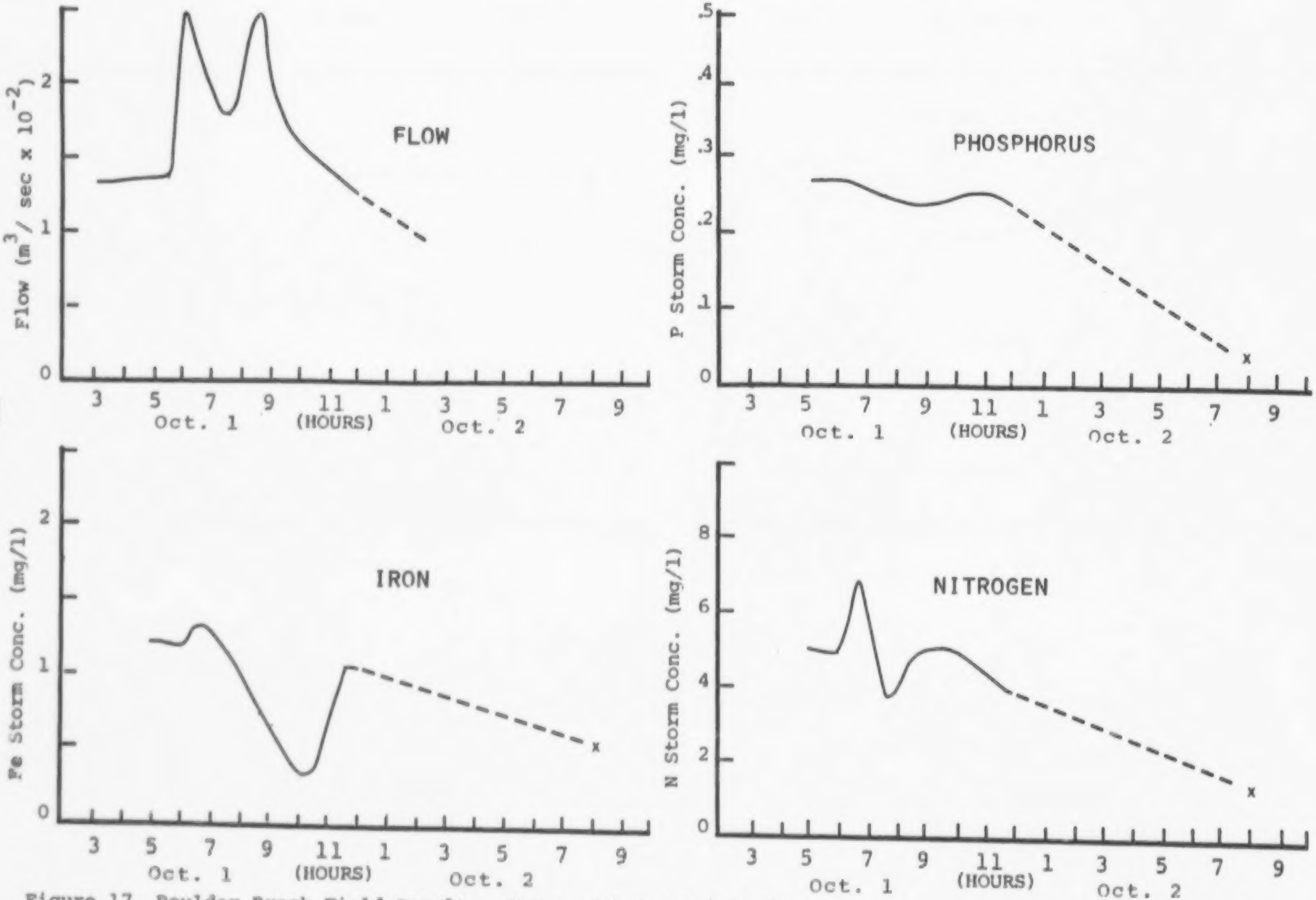

Figure 17. Boulder Brook Field Results, Storm of 1 October 1978. All values represent combined storm flow and base flow. Dashed lines represent interpolation between last two samples.

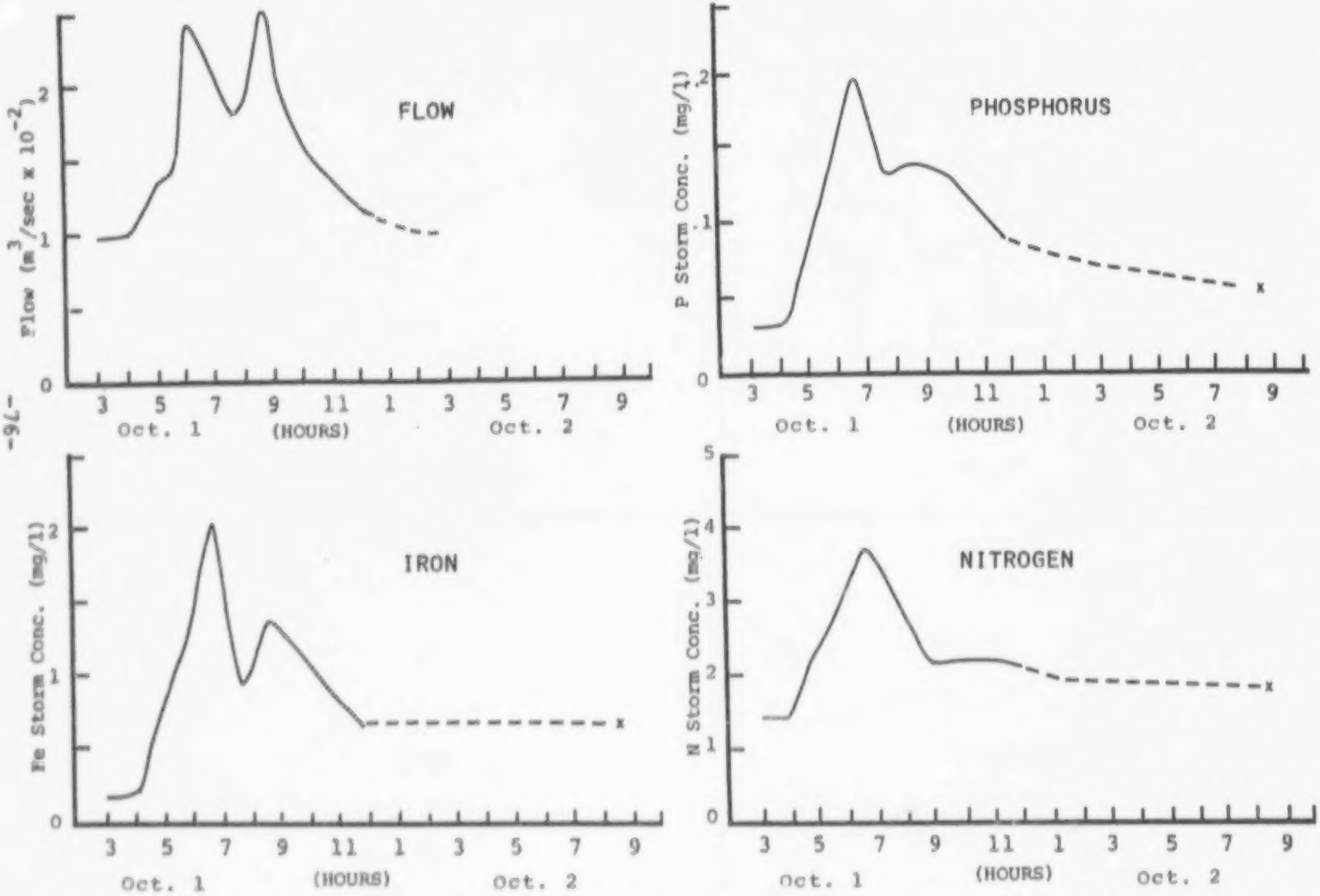

Figure 18. Boulder Brook Storm Data Corrected by Removing Base Flow, 1 October 1978. Dashed lines represent interpolation between last two samples.

6.0 LAKE BIOLOGY

This section of the report is aimed at the description of aquatic botany in the lake system. The reponse of the plant community to $KMnO_4$ treatments and to dredging is treated in detail.

6.1 Phytoplankton

6.1.1 Phytoplankton Genera in Morses Pond

The number of phytoplankton genera seen in Morses Pond for the period 1974 to 1979 inclusive is 132. The overall breakdown by genera is:

- 62 green algae, of which, 10 are flagellates;
- 32 diatoms
- 15 blue green algae;
- 11 golden browns
- 6 euglenoids
- 4 dinoflagellates;
- 2 group uncertain

This listing does not include epiphytic algae growing on the stems and other portions of the macrophytes nor does it include the dominant periphyton Schizogonium.

The data base available for analyzing periphyton consists of surface algal counts for the summers of 1974 to 1976 and 1979. For the years 1977 and 1978, phytoplankton monitoring occurred in the summers but also included monthly sampling in the other seasons. Replicate samples were taken on each sampling date.

For sampling purposes, summer is defined as the period from the time the water temperature reaches 18.5°C (65°F) until the end of the recreation season on the first Monday in September. Sampling procedures are discussed in Appendix C. The sampling frequency is presented in Table 16.

Given a total of 9 sampling periods, the phytoplankton community can be subdivided into 6 classes based on frequency of occurrence. They are described below.

Constant - These 12 algal genera are present during all 9 sampling periods.

Frequent - These 22 algal genera are present for 7 or 8 of the sampling periods.

Common - These 23 algal genera are present in 4 to 6 of the sampling periods.

Common in Summer - These 5 algal genera are present during 4 to 6 summers but do not show up in other seasons.

Uncommon - These 33 algal genera appeared during only 2 or 3 sampling periods.

Rare - These 37 algal genera appeared during only one sampling period. In fact 22 of these genera appeared in only one sample.

Table 17 lists the genera present in each of these classifications.

Table 16 - Sampling Data for Phytoplankton

Season	Year	Sampling Days	Number of Genera
Summer	1974	17	60
Summer	1975	48	60
Summer	1976	66	77
Winter & Spring	1977	13	46
Summer	1977	36	58
Fall & Spring	1978	10	58
Summer	1978	42	56
Fall & Winter	1978	7	45
Summer	1979	50	73

6.1.2 Phytoplankton and Visibility

One reason for an interest in phytoplankton in lakes is that of the impact on visibility in the water. The suspended algae act as light scatterers and thus are one of the factors that reduce visibility. Visibility is a key concern in terms of public safety

TABLE 17. Algal Genera in Morses Pond by Frequency of Occurance. 1974-1979

CONSTANT.

Green Algae

Botryococcus
Chlorella
Closterium
Coelastrum
Cosmarium
Scenedesmus

Blue-Green Algae

Anacystis
Oscillatoria

Diatoms

Asterionella
Fragilaria
Navicula
Tabellaria

FREQUENT.

Green Algae

Ankistrodesmus
Chlorococcum
Gloeocystis
Oocystis
Pediastrum
Phytoconis
Schroderia
Shaerocystis
Staurastrum

Blue-Green Algae

Anabaena

Diatoms

Amphora
Cocconeis
Cymbella
Diatoma
Gomphonema
Pinnularia
Stauroneis
Synedra

Dinoflagellates

Gymnodinium

Golden-Brown Algae

Dinobryon
Mallomonas

Euglenoids

Euglena

COMMON.

Green Algae

Crucigenia
Elaktothrix
Golenkinia
Palmella
Planktosphaeria
Ulothrix
Westella

Dinoflagellates

Ceratium

Green Flagellates

Chlamydomonas
Volvox

Blue-Green Algae

Gomphosphaeria

Goldon-Brown Algae

Chromulina
Chrysococcus
Synura

Diatoms

Achnanthes
Cyclotella
Diatomella
Eunotia
Gyro/Pleurosigma
Melosira
Meridion
Nitzschia

Euglenoids

Lepocinclis

COMMON IN SUMMER.

Green Algae

Dictyosphaerium

Dinoflagellates

Peridinium

Blue-Green Algae

Aphanizomenon

Golden-Brown Algae

Trachelomonas

Diatoms

Frustulia

TABLE 17. Algal Genera (Continued)

UNCOMMON.

Green Algae

Actinastrum
Asterococcus
Closteridium
Closteriopsis
Desmidium
Euastrum
Kirchneriella
Micractinium
Mougeotia
Nephrocytium
Pleurotaenium
Selenastrum
Tetraedron
Tetraspora
Zygnema

Green-Flagellates

Chlorogonium
Gleomonas
Pandorina
Pleodorina

Blue-Green Algae

Nodularia
Nostoc

Diatoms

Actinella
Caloneis
Diploneis

Dinoflagellates

Glenodinium

Goldon-Brown Algae

Chrysocapsa
Epipyxis
Ochromonas
Tribonema
Uroglenopsis

Euglenoids

Euglenopsis
Phacus

Group Uncertain

Cryptomonas

RARE.

Green Algae

Binuclearia
Docidium
Haematococcus
Hyalotheca
Nannochloris
Netrium
Ourococcus
Pachycladon
Poleydriopsis
Psuedoulvella
Radiococcus
Spirogyra
Stichococcus
Tetradesmus

Green-Flagellates

Carteria
Eudorina
Gonium
Lobomonas

Blue-Green Algae

Agmenellum
Amphithrix
Coccochloris
Dactylococcopsis
Lyngbya
Phormidium
Rhabdoderma
Spirulina

Diatoms

Amphipleura
Camphylodiscus
Chaetoceros
Cyclonexis
Entomoneis
Gomphoneis
Rhizosolenia
Surirella

Golden-Brown Algae

Uroglena

Euglenoids

Sphenomonas

Group Uncertain

Chilamonas

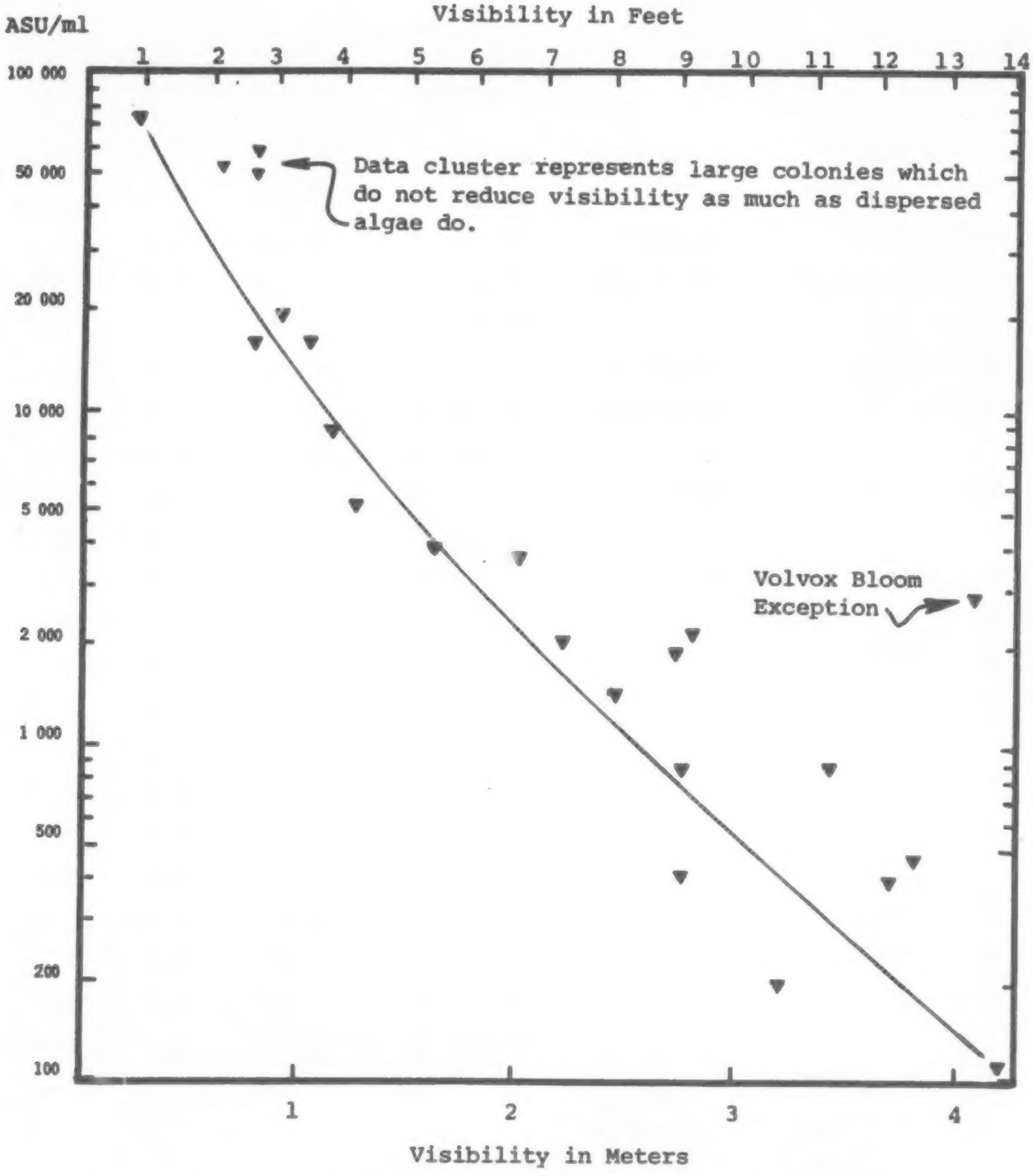

Figure 19. Visibility Versus Phytoplankton Biomass in ASU/ml.

TABLE 18. PHYTOPLANKTON DOCUMENTATION FOR FIGURE 19.

Lake	Town	Date	ASU/ml	Visibility	
				m	ft
Pillings Pond	Lynnfield	31 Aug 77	72,850 *	0.5	1.0
" "	"	28 Apr 77	52,600	0.6	2.12
Rosemary Lake	Needham	22 Jul 75	8,800	1.1	3.7
Lake Quannapowitt	Wakefield	7 Jul 77	50,100	0.8	2.6
" "	"	21 Jul 77	55,200	0.8	2.6
Dyerwood Pond	Foster,RI	20 Jul 76	16,800	0.8	2.7
Barrett Pond	Leominster	14 Jun 79	3,900	1.6	5.3
" "	"	2 Aug 79	19,700	0.9	3.0
Hinkley Pond	Medfield	7 Jul 79	15,600	1.1	3.5
" "	"	14 Aug 77	5,373	1.3	4.2
Morses Pond	Wellesley	22 Jul 79	3,711	2.0	6.6
" "	"	6 Aug 79	1,894	2.8	9.25
" "	"	21 Jul 79	420	2.8	9.1
" "	"	25 Aug 79	2,170	2.8	9.25
" "	"	25 Jul 75	194	3.2	10.5
" "	"	2 Jul 75	112	4.2	13.75
" "	"	4 Jun 75	862	2.7	9.0
" "	"	23 Jun 75	455	3.8	12.5
" "	"	7 Jul 75	2,800 †	4.11	13.4
" "	"	27 Jul 75	857	3.4	12.2
" "	"	6 Jul 76	399	3.7	12.2
" "	"	29 Aug 77	1,461	2.4	8.0

* Maximum count

† Exception to rule due to *Volvox* bloom

at recreational beaches. Massachusetts law mandates the visibility be at least 1.25 m (4 feet) for public swimming.

Visibility in water is affected by three major components; (1) dissolved substances which color the water, (2) clays and other particulates suspended in the water (measured as turbidity), and (3) phytoplankton suspended in the water. When two or more of these components are acting together, each component has to be evaluated in order to properly define the nature of the visibility problem.

In dealing with the algal component of visibility loss, there are three common measures of the phytoplankton community:

1- chemical testing for chlorophyll *a*;

2- phytoplankton cell counts or organism counts; and

3- phytoplankton biomass estimation using Areal Standard Units per milliliter (ASU/ml) or Cubic Standard Units per millilter.

For evaluation of chlorophyll *a*, Rast and Lee (1978), page 291, show data of chlorophyll *a* versus secchi disk visibility in meters. Using the curve from Rast and Lee and selecting a representative chlorophyll *a* value of 11 g/l, the range of expected values of visibility is 0.84 m (2.7 feet) to 3.0 m (9.8 feet). This range is so great, one could not tell if visibility loss is due to phytoplankton, clays in suspension or colored water. Thus as a practical visibility management tool, chlorophyll *a* is really quite meaningless.

The same is true of cell counts and organism counts. Cell size varies greatly for different growth conditions. Add the variations in colony size and it is easily perceived that cell or organism counts have little value when dealing with practical problems involving visibility.

Thus by process of elimination, the resolution of visibility related problems falls on some type of biomass estimation technique. In the course of this study, investigation of the use of ASU/ml as a visibility predictor has been made using numerous ponds and lakes in Eastern Massachusetts. The observed range of phytoplankton biomass for evaluation purposes ranges from 100 ASU/ml to 72,800 ASU/ml. Given this wide range, a semi-log plot of the data is required. This is shown on Figure 19 with the data base documentation in Table 18. Note that all the data are confined to summer conditons when green and blue-green algae dominate. Note further that cloud cover, water color and suspended inorganics all affect visibility. Thus the data selected for this analyis were screened as much as possible to reduce the effects of other variables affecting visibility. Most of the data represent zero percent cloud cover. It is important to note that visibility is averaged for two to three sun angles and the algal data is the average of two grab samples taken at depth of about 15 cm (6 inches) in the same general area of the lake. See Appendix C for a full discussion on algal sampling technique. It has been our experience that the natural patchiness of phytoplankton in water requires at least two algal counts to ease the interpretation of the data relative to both visibility and to phytoplankton community behavior. Samples from surface "slicks" were specifically avoided due to known enhancement of algal counts.

In reviewing the phytoplankton-visibility problem, there is one notable exception to the rule. That is when a bloom of _Volvox_ occurs, visibility is not apparently affected. The reason for this is the character of the _Volvox_ colony. Under the microscope, the colony generates a large ASU count due to the large size of the colony. However, the colonies are essentially hollow and the optically dense portions of the cells have a good separation. Thus the biomass number becomes large with little impact on visibility.

It should also be pointed out that when blue-green algal colonies are large, the impact of the colony is less than the impact would be if the cells or chains of cells were distributed in the water. This is noted for a cluster of data points on Figure 19.

6.1.3 Natural Algicides

Since _Volvox_ was discussed in the last section, this seems to be a logical place to discuss the natural algicide released by this algae. Harris and Caldwell (1974) showed that _Volvox_ releases a natural algicide. The 1975 bloom of _Volvox_ confirms the algicidal properties of chemicals released by the die off of the _Volvox_. Table 19 documents the _Volvox_ bloom and the response of the rest of the phytoplankton community. It is the reduction of the rest of the phytoplankton community that confirms the algicidal action due to _Volvox_.

On July 7, the average _Volvox_ count was 1439 ASU/ml. This was the peak value recorded during the _Volvox_ bloom and values dropped off rapidly after this. A total algal count of 455 existed prior to the start of the _Volvox_ bloom on June 23. On July 7, the total count (excluding _Volvox_) dropped to 26.6 ASU/ml. On July 9 it equaled 26.2 ASU/ml and as late as July 17, near the end the of _Volvox_ population in the community, total algae minus _Volvox_ was 18.4 ASU/ml. Algal levels began recovery by July 25. _Volvox_ bloomed again on August 27. However, follow-up data are lacking because field work terminated on August 29. _Volvox_ blooms have not been observed in other years.

TABLE 19. *VOLVOX* EFFECTS ON OTHER ALGAE, 1975.

Date	VOLVOX (ASU/ml)	Other Algae (ASU/ml)
June 23	0	455
July 2	67	45.3
July 7	1439	26.6
July 9	19.1	26.2
July 11	351	9.4
July 17	5.9	18.4

6.1.4 Prediction of Algal Blooms

Prediction of algal blooms is a critical item for managing eutrophic lakes and for managing water supply reservoirs. Given that an algal bloom can take as little as three days, and given that algae are more susceptible to chemical control in the pre-bloom stages; daily algal counts are a required management step at critical times.

Nelson (1941) pointed out that critical temperatures for plant activity were found to lie close to 5°, 10°, 15°, 20°, and 25°C (41°, 50°, 59°, 68°, and 77°F). Monie (1956), in his experience in managing reserviors, confirmed that these temperatures were valid for phytoplankton bloom prediction. The five years of daily management of Morses Pond confims that these critical temperatures do, in fact, influence algal blooms (See Table 20). Thus a heavy reliance on water temperature information has been made in predicting and preventing algal blooms in Morses Pond. Since the key goal of this program has been to control blue-green algal blooms, the management focus has been concentrated during the times when the temperature approached 20°C (68°F) and 25°C (77°F). No blooms of nitrogen-fixing blue-green algae *Anabaena* and *Aphanizomenon* have been observed below those temperatures. However, in November of 1978 *Anabaena* did reach a pre-bloom level of 330 ASU/ml while the water temperature passed through the critical temperature of 10°C (50°F). Drost-Hansen (1974) further discusses critical temperatures related to biological activity.

It is mandatory that lake management begin as the water temperature reaches 18°C (65°F) because:

1- nitrogen-fixing blue-green algae generally become a problem at 20°C (68°F);

2- the water can reach that temperature at any time between April and June in Eastern Massachusetts; and

Table 20. Algal Blooms and Temperature Relationships, Morses Pond, 1975 - 1979.

Date of Bloom Initiation	Genera	Morning Water Temp.* °C Preceeding Day	Morning Water Temp.* °C Day of Bloom	Average Temp. Deviation from Critical Temp. °C.
29 May 75	Anabeana	20.0	20.8	0.40
7 Jul 75	Volvox	25.6	26.1	0.85
8 Aug 76	Aphanizomenon	24.4	25.0	0.30
16 Aug 77	Chlorella	26.7	25.6	1.15
6 Nov 78**	Anabaena	10.3	10.8	0.55
19 Jul 79	Anacystis	26.7	25.6	1.15
21 Aug 79	Anabaena	20.0	23.3	0.85

Mean Deviation = 0.75°C.

* Tempature Accuracy ±0.3°C.

** Five Day Interval Between Samples.

3- nitrogen fixation can greatly increase the nutrient loading in a nitrogen limited lake, thus stimulating algal potential for the rest of the year.

If lake management only begins a week before the recreation season starts, nitrogen fixation could have already so over-loaded the lake that control of algae and visibility might almost be precluded.

6.1.5 Phytoplankton Response to $KMnO_4$

In the discusion of Task 7, Chemical Management; Section 3.0 contains a general introduction to the theory behind the use of $KMnO_4$ in open lake waters. Specifically, $KMnO_4$ is being used to convert the dissolved iron and iron in organic complexes into an oxidized state such that the iron is no longer available to the phytoplankton community. Appendix A reprints the key reference of Morton and Lee (1974) which presents the concept that iron is a key micronutrient whose presence favors the blue-green algae over the green algae. Table 2 and and Table 21 present the results of five Summers of $KMnO_4$ use versus the 1974 recreational season when $KMnO_4$ was not in use.

If 1979 is exluded from the discussion because of the impact of dredging, Figure 20 and Tables 2 and 21 show that compared to 1974, $KMnO_4$ use in the summer season lowered:

- average total algal counts (ASU/ml) by 61%,
- average blue-green algal counts by 26%,
- average *Anabaena* by 40%,
- average *Aphanizomenon* by 96%,
- average green algal counts by 42%,
- average diatom algal counts by 80%,
- average euglenoids by 80%,
- average dinoflagellates by 28%,

while having almost no impact on the average golden brown algae.

In *every* year $KMnO_4$ was used there was a significant reduction in:

- total algae,
- blue-green algae,
- diatoms, and
- euglenoids.

The average reduction in green algae, while arithmetically real, may not have been significant in 1976 and 1977. For the dinoflagellates, their count was actually elevated in 1975 and depressed in other years. The golden brown algae seem to be either very prolific, as in 1976 and 1977, or almost absent, as in 1975 and 1978. The golden brown algal population seems to

Table 21. Pre-(1974) and Post-(1975-1979) $KMnO_4$ Phytoplankton Statistics for Morses Pond.

	1974	1975	1976ζ	1977†	1978	1979ξ	1979 Ψ
Average Total Algae (ASU/ml)	1247	167	792	808	155	1743	2863
Average Green Algae (ASU/ml)	493	114	448	456	121	198	375
Average Blue-Green Algae (ASU/ml)	219	14.4	30.1*	77.0	4.3	1231	2309
Average Diatoms (ASU/ml)	241	5	48	219	12	53	409
Average Golden-Brown Algae (ASU/ml)	104	3	219	172	6.1	138	60
Average Euglenoids (ASU/ml)	33	0.4	13	12	0.24	19	18
Average Dinoflagellates (ASU/ml)	31	42	28	6.5	12	1.3	1.1
Average Sampling Spacing (Days)	4.78	2.05	1.91	2.66	2.48	2.14	2.00

* *Aphanizomenon* was not present until a major storm occurred in August. Visibility dropped about three feet as the water turned yellowish-brown indicating significant iron additions. Then *Aphanizomenon* appeared at significnt levels.

ζ The 1976 $KMnO_4$ treatment was in early May. Thus the statistics include a late Spring period of enhanced productivity. In most other years, the treatment was delayed until June by cooler weather and this late Spring productivity was not included in the statistics.

† The 1977 algal counts generally ran higher than those of 1975. *Anabaena* was left in the lake longer at the start of the season and this combined with the apparent lower water milfoil crop could have generally encouraged phytoplankton.

ξ Dredge working in an isolated part of the lake (pre-August 2).

Ψ Dredge working in the main circulation patterns of the lake (post-August2) .

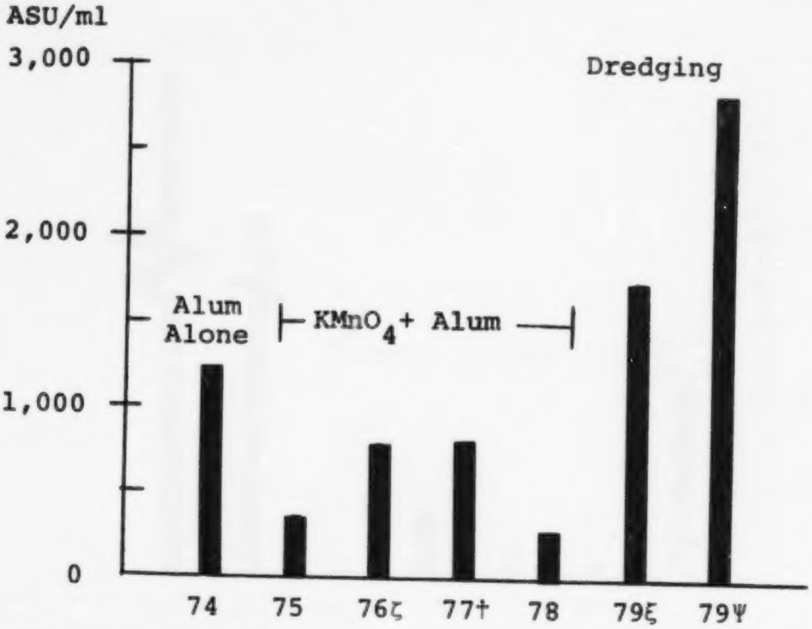

Figure 20a. Average Total Algae, Morses Pond, 1974 to 1979. For footnotes see Table 21.

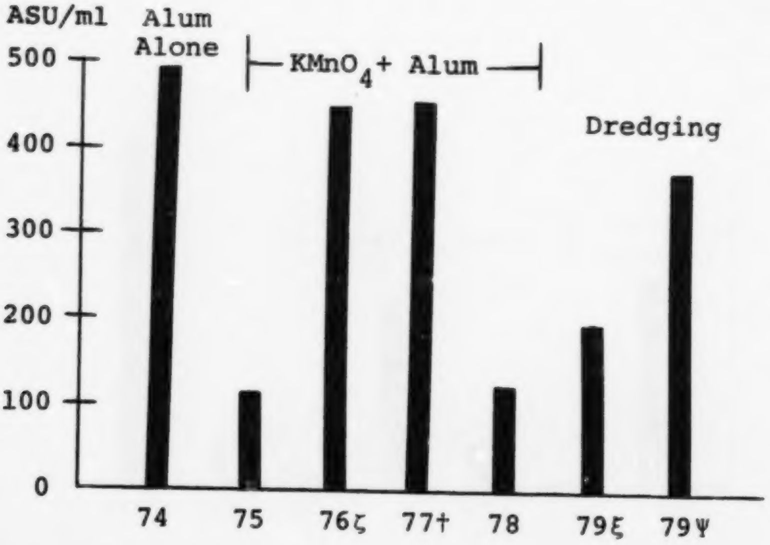

Figure 20b. Average Green Algae, Morses Pond, 1974 to 1979. For footnotes see Table 21.

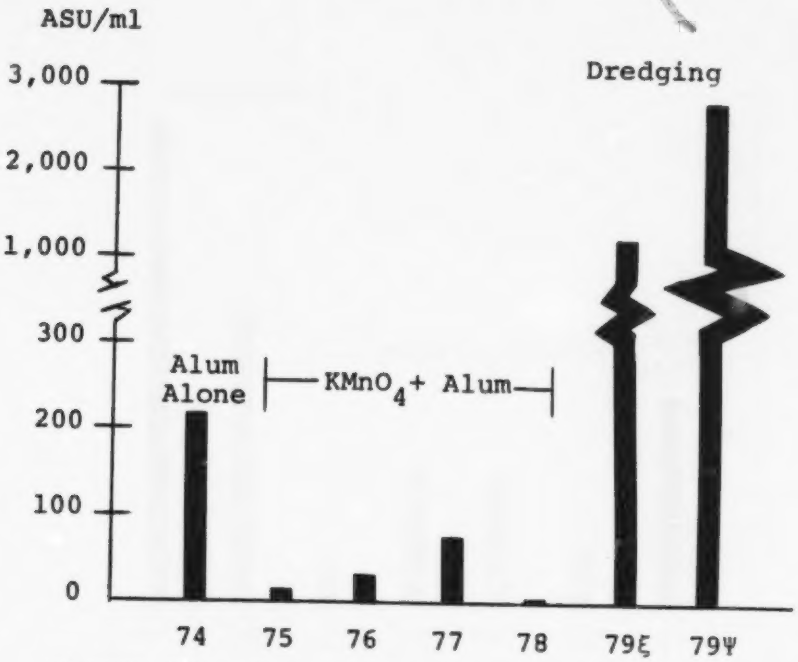

Figure 20c. Average Blue-Green Algae, Morses Pond, 1974 to 1979. For footnotes see Table 21.

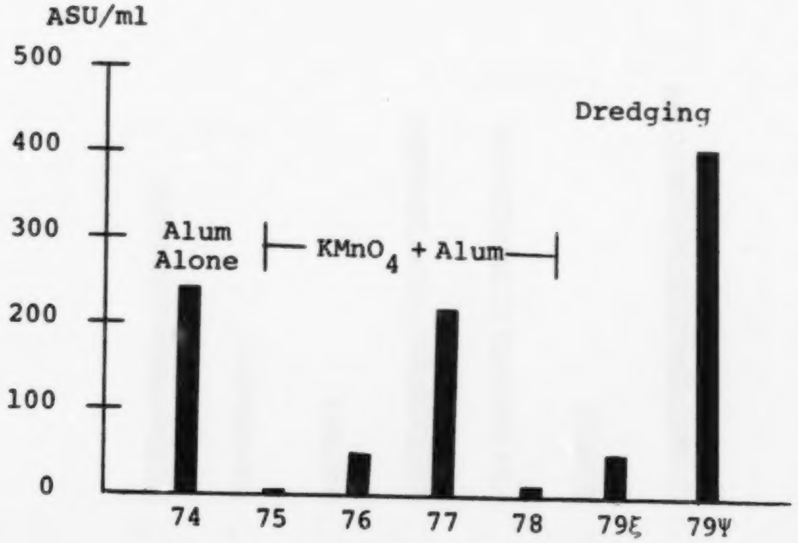

Figure 20d. Average Diatoms, Morses Pond, 1974 to 1979. For footnotes see Table 21.

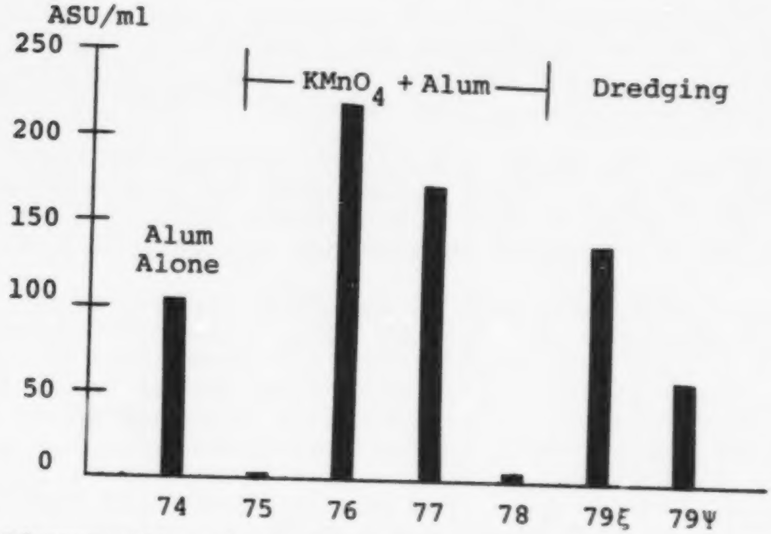

Figure 20e. Average Golden-Brown Algae, Morses Pond, 1974 to 1979. For footnotes see Table 21.

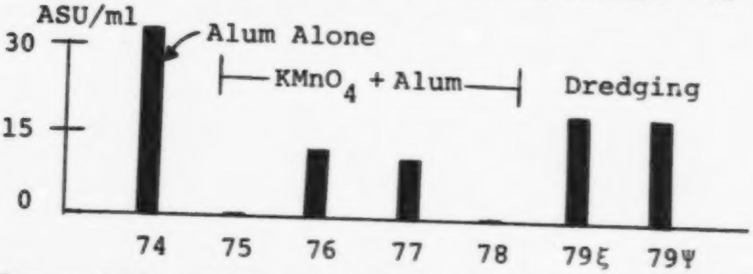

Figure 20f. Average Euglenoids, Morses Pond, 1974 to 1979. For footnotes see Table 21.

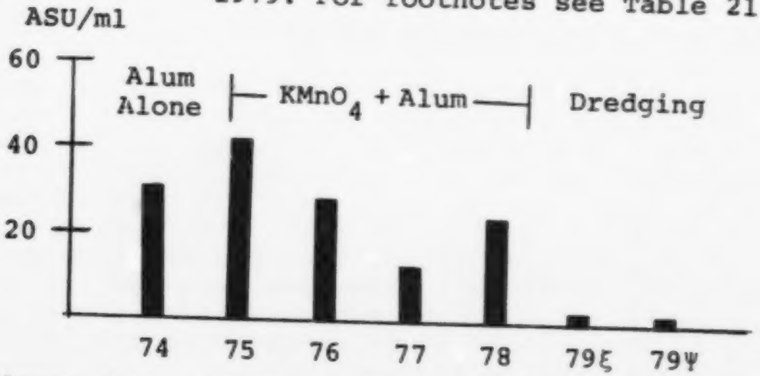

Figure 20g. Average Dinoflagellates, Morses Pond, 1974 to 1979. For footnotes see Table 21.

behave in a fashion parallel to the green algae in iron deficient environments. It is interesting that the use of $KMnO_4$ impacts the blue-greens, the diatoms and the euglenoids with roughly the same percent reduction of biomass as measured in ASU/ml.

The above discussion shows a seasonal response of the phytoplankton community to a sudden loss of iron due to $KMnO_4$ treatment. On a shorter time scale, there is also some evidence for phytoplankton response to a sudden *increase* in iron.

In mid-August 1976, the edge of hurricane Belle passed over Eastern Massachusetts and brought heavy rains (109.2 mm, 4.30 inches) for a five day period. Jennings Pond, just above Morses Pond, overturned and slowly flushed into Morses Pond. The influx of iron from the hypolimnetic waters of Jennings Pond, and possibly from the wetlands in the drainage basin, was so great that Morses Pond turned a light yellow-brown color. *Aphanizomenon* appeared within three days, and one day later had reached pre-bloom levels, thus requiring a $CuSO_4$ treatment. It should be noted that the water temperature was just nearing 25°C (78°F) as the *Aphanizomenon* began to be a problem. This demonstrates both the role of iron and the role of temperature in affecting algal blooms. Additional details are presented at the end of Section 2.0 of this report.

In summary, the chemical testing results (Section 5.4) show that $KMnO_4$ converts iron into a form not available to biological systems. The diatoms, the euglenoids, and the blue-green algae all respond with reduced biomass and total biomass as measured in ASU/ml is thus significantly reduced. It is important to note that *Aphanizomenon* responds dramatically to removal of iron while *Anabaena* will still require use of $CuSO_4$ for total control.

6.1.6 Phytoplankton Response to Dredging

The 1979 algal data allow an evaluation of dredging under two scenarios. During the spring and the early summer, the dredge was working in Areas I and II as shown in Figure 8. These areas are somewhat isolated from the main circulation pattern of the lake (See Figure 2). Thus only on windy days did much of the dredging plume affect the main body of the lake. During the late summer, the dredge moved into Area IV and thus the dredging plume was directly and continuously affecting the main body of the lake. Again referring to Figue 20 and Tables 2 and 21, the results of the dredging on phytoplankton, as compared to the 1975-1978 recreation seasons are as follows.

During the early stage of dredging in 1979, dinoflagellates and green algae were suppressed, diatoms remained generally stable, visibility was maintained in excess of 3 meters (12 feet), while euglenoids doubled, total algal biomass in ASU/ml increased by a factor of 3.6, and blue-green algae increased by two orders of magnitude. The chemical treatment program during this initial phase of dredging consisted of the usual single treatments of $KMnO_4$, $CuSO_4$ and alum to get the lake under control. However, additional treatments were required to keep the lake under control due to the added growth stimulated by dredging. The total chemical control program during this year of dredging as compared to non-dredging years is defined is Table 22.

Once the dredge moved into the main part of the lake, dredging further affected phytoplankton. Dinoflagellates remained depressed, euglenoids didn't change, diatoms now increased by almost an order in magnitude, green algae increased by 42% over the non-dredging base period, and total algal biomass increased by another 60%. Visibility decreased to 2.3 m (7.5 feet). Again a $CuSO_4$ treatment was required to control algal blooms. It was decided not to use alum because the continuous turbidity from the dredging would prevent any sustained enhancement of visibility. As can be seen, dredging in the summer carries with it a significant enhancement of algal bloom potential. Thus it is recommended that funds be allocated for monitoring and chemical treatment of a lake if it is desired to use a lake for contact recreation while dredging is underway.

6.2 Periphyton

The major periphyton genus in Morses Pond is Schizogoium. In the spring occasional patches of Spirogyra are seen, and in August 1977 some diffuse gelatinous clouds of Mougeotia were seen. However, Schizogonium is clearly dominant and discussion will be confined to this genus.

The first item of note about this periphyton is that the mats are several centimeters thick in places in Morses Pond. In hot weather (>35°C, 95°F) the algal mats rise to the surface and drift around the pond. In 1977, during the citizen clean-up day, it was noted that in shallow areas in the large easterly cove the periphyton and leaf accumulations were interlayered representing the annual accumulation of each during the year.

The accumulated mass of periphyton was evaluated at the end of November, 1977 and the dry weight of periphyton per square meter ranged from 320 g/m2 to 951 g/m2 with an average of 642 gm/m2 in depths less than 1.8 m (6 feet). In depths greater than 1.8 m, the results were 60 g/m2 to 103 g/m2 with an average of 87 g/m2. This clearly documents the depth dependency of these plants. Since the water was clear in the growing season for the two years prior to the field survey, light was not limiting. The periphyton mats are so thick and extensive no significant seasonal variation is expected. Sampling and laboratory techinques are defined in Appendix C.

TABLE 22. - Chemical Application Program, Morses Pond 1975 - 1979

Year	Date	Treatment
1975	June 11	partial $CuSO_4$*
	June 12	$KMnO_4$
	June 16 - 18	Alum
1976	May 11	Partial $CuSO_4$*
	May 12	$KMnO_4$
	May 19 - 21	Alum
	June 24	$CuSO_4$
	August 16	$CuSO_4$
1977	May 27	$KMnO_4$
	June 1 - 3	Alum
	June 15	$CuSO_4$
	June 25	Alum (1/3 treatment)
	August 20	$CuSO_4$
1978	June 8	$KMnO_4$ (incomplete) hypolimnetic treatment)
	June 12 - 14	Alum
	July 5	$CuSO_4$
	July 17	$KMnO_4$ (completion) hypolimnetic treatment)
	July 18	Alum (1/3 treatment)
1979	April - September	Dredging
	May 23	$CuSO_4$
	June 4	$KMnO_4$
	June 6, 11, 12	Alum
	July 14	$CuSO_4$
	July 23	$CuSO_4$
	July 26, 27	Alum (2/3 treatment)
	July 28	$CuSO_4$
	August 23	$CuSO_4$

* In partial $CUSO_4$ treatments, only part of the lake was treated.

When evaluating the biomass of periphyton, relative to the rest of the plant biomass in Morses Pond, literature values were used for the other plants, Boyd (1967). The results show that the accumulated periphyton is about 80% of the dry weight of the plant system, 85% of the weight of nitrogen in the system, and 45% of the phosphorus weight of the system.

Since 1977, there has been no effort to further quantify the periphyton in Morses Pond. However, the general observation is that periphyton is decreasing in Morses Pond. The evidence for this decrease in periphyton is that more barren areas are now observed in the pond and only tree leaves and pondweed fragments are found in some areas where periphyton coverage was once 100%.

Three sampling events for the chemical composition of periphyton occurred during this study. The results are presented in Table 23. The most important result of this chemical testing is related to N/P ratio analysis. This ratio analyis shows that N/P for Schizogonium is quite variable ranging from 18.3 to 418.3. This wide range may be due to interaction with substrata of variable composition. The importance of the results, regardless of the wide variation, is that periphyton mats in this lake clearly store more nitrogen than phosphorus. The implications of this will be discussed further in Section 8.0

As for response of the periphyton to chemical treatment, there is simply not enough data to allow reasonable conclusions to be drawn. One could only postulate that the increase in light penetration due to enhanced water clarity may result in a competitive advantage of macrophytes over periphyton. This might account for the general observation of decreasing periphyton coverage over the years. Another factor that could also account for the decreasing periphyton is the covering of the periphyton mats by the floc resulting from the alum treatments. This is more likely to be a factor in the deeper portion of the pond where the alum floc tends to become concentrated due to waves and currents removing the floc from shallow areas. To document the environmental requirements of Schizogoium and its full response to chemcial treatment, a multi-year research program would be required.

The response of periphyton to dredging is readily seen in Figure 21. In dredged areas, the periphyton mats were almost totally removed. In the areas adjacent of the dredging, periphyton was clearly depressed by burial by sediments transported by the dredging plume. What is very interesting is that periphyton was also depressed in the easternmost cove surveyed, and this latter cove was hardly impacted at all by the dredging. The reason for this latter area having a reduced periphyton population is unknown, but may reflect the generally observed decrease in

Table 23. Chemical Composition of Periphyton In Morses Pond. Sample locations are shown on Figure 20.

Stations	1	1	2+3*	4+5*
Date	Jan. 78	Mar. 78	Aug. 78	Aug. 78
Total Phosphorus (mg/l)	440	49	722	1,650
Ortho-Phosphorus (mg/l)	-	-	61	168
Total Kjeldahl Nitrogen (mg/l)	8,050	20,470	54,500	50,500
Ammonia Nitrogen (mg/l)	480	-	1,750	1,725
Nitrate Nitrogen (mg/l)	36	28	340	180
Nitrite Nitrogen (mg/l)	1	1	10	10
Iron (mg/l)	-	-	9,480	6,400
Copper (mg/l)	-	-	1,315	117
Aluminum (mg/l)	-	-	3,950	1,065
Percent Solids	-	-	14	15
Location of Plants	bottom	bottom	bottom	floating

* Value is average of two separte samples, variations in results were small.

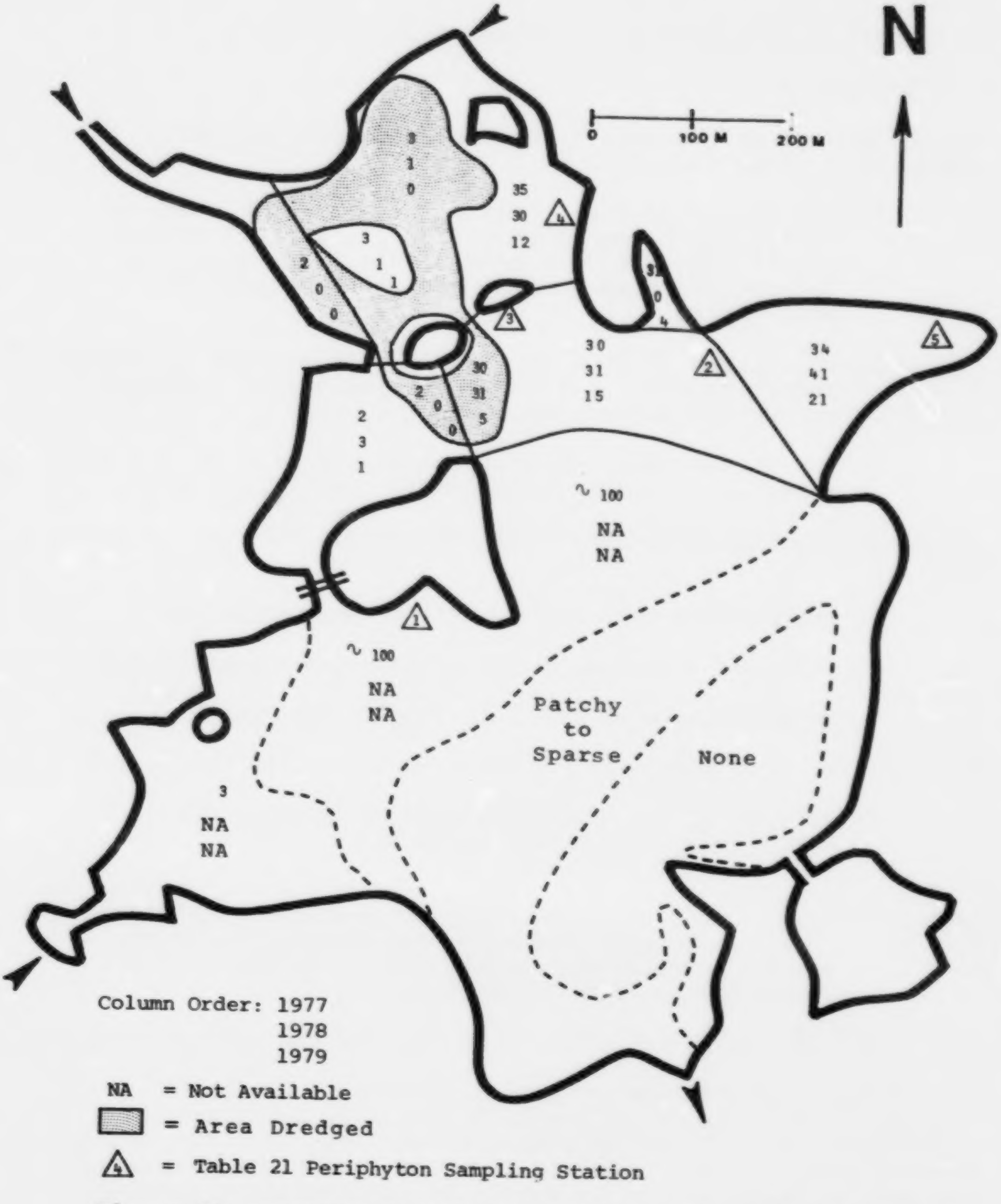
N
0
100 M
200 M
3
1
0
35
30
12
4
3
1
1
2
0
0
31
0
4
3
30
31
15
2
34
41
21
5
30
31
5
2
0
0
2
3
1
~ 100
NA
NA
1
~ 100
NA
NA
Patchy to Sparse
None
3
NA
NA
Column Order: 1977
1978
1979
NA = Not Available
▨ = Area Dredged
△ = Table 21 Periphyton Sampling Station

Figure 21. Percent Periphyton Coverage of Morses Pond. No data recorded in 1978 and 1979 in the main body of the lake because no significant impact of dredging was anticipated.

periphyton in the main part of the pond.

6.3 Macrophytes

The aquatic plant problems in Morses Pond have several components. These include:

1- the spread of high profile (plants which reach or nearly reach the water surface) submerged aquatic plants into the main body of the lake, such plants interfering with boating and other recreational activities;

2- the spread of floating leaved plants, such as yellow and white water lilies and variable leaf pondweed, throughout Morses Pond; and

3- the encroachment of emergent plants into Morses Pond, especially in the northernmost area of the pond.

The major benefits associated with the submerged aquatic plants are:

1- competition with phytoplankton for nutrients;

2- offering a sheltered habitat for zooplankton; and

3- offering a potential food supply for fish.

The floating leaf plants are considered a problem because:

1- they directly release metabolism by-products into the water, which stimulate algal bloom potential in the main part of the lake;

2- they create a microenvironment which favors duckweed cover, which in turn allows anaerobic conditions to evolve in protected areas, thus favoring nutrient release from the sediments; and

3- they build up bottom muck faster than submerged plants.

With respect to this latter point, there is a dearth of literature on rates of sediment accumulation on submerged vegetation versus floating leaved vegetation. Thus the concept of greater sedimentation rates in floating leaf plant communities can only be demonstrated by review of sedimentation principles and from case histories.

Concerning sedimentation mechanisms there are four factors that increase sedimentation in areas dominated by floating leaf plants versus areas dominated by submerged aquatic plants. The first of these mechanisms is the effect of the plants on currents. Submerged plants bend with the currents and as such don't slow the currents as much as the floating leaved plants which resist the current. This enhanced ability to slow currents means more sedimentation. The second factor is dry fall. Particulates falling onto the water surface must pass through the surface tension film at the surface before the particles can fall through the water column and join other sediments. In the case of floating leaved plants, this dry fall remains trapped by the dense surface leaves and is thus retained in the area. For submerged plants, the dry fall can drift from the site of water contact and deposition can occur elsewhere in the lake.

The third mechanism is related to enhanced phytoplankton growth in the areas of floating leaved plants. In 1975, phytoplankton sampling included one site where submerged plants dominated and a second site where water lilies averaged 10% surface coverage. The five sampling events from mid-May to the end of July showed that the water lily area always had more phytoplankton and that on the average was 5 times greater in phytoplankton biomass as measured in ASU/ml. This enhanced phytoplankton coverage was probably due to the nutrient recycling associated with the water lilies and represents a source of additional sediment accumulation.

The fourth mechanism is a subtle one. Anyone who is out on a lake with water lilies, can observe the warm water under the lily pads. This warm water has a greater fluidity and lower viscosity and thus allows particles to settle out at a greater speed (Hardy, 1967). Thus the enhanced temperature allows greater accumulation of both organic and inorganic particles.

The filling of Carr's cove on Cayuga Lake in New York is a good case history. Water lilies were introduced into the cove about 1885, and at that time water depths allowed barges to load in the cove. By 1920 the water lily coverage was extensive and significant areas were quite shallow. By 1950, the accumulated water lily muck was such that, in areas that were formerly open, the water was no longer deep enough for a rowboat. This clearly represents a dramatic filling associated with water lily introduction. This site would represent a good area for a research project to document the actual sedimentation rate associated with water lilies.

Returning to Morses Pond, the emergent plants are a major threat to Areas I and II as shown in Figure 8 because:

1- they are rapidly converting open water areas into marsh;

2- they increase evapotranspiration, thus increasing water losses;

3- they build up organic sediments faster than the submerged and floating leaf plants;

4- where they encourage duckweed cover, the emergents again favor nutrient releases into the main part of the lake; and

5- once established they block shoreline activities requiring access to open water.

Table 24 presents the species recorded during aquatic plant survey of Morses Pond. The major plants in the lake are water milfoil (Myriophyllum heterophllum Michx.), spatterdock and white water lilies, coontail (Ceratophyllum demersum L.), variable leaf pondweed, Robbins' pondweed (Potamogeton robbinsii Oakes.), and slender arrow-head (Sagittaria graminea Michx.). The variable leaf pondweed has generally been spreading in Morses Pond. Town employees have removed major patches of this plant by removing entire plants, roots and all. Such removal has been quite successful. Since the distribution of this plant is quite patchy and a low percent of total coverage, it will only be noted here that continued removal efforts will be required to keep this plant from taking over major areas of the pond.

For each of the remaining major plants, a map presenting percent coverage for 1977, 1978, and 1979 is presented. The dotted area shows the area dredged on all the plant maps. It should be stressed that the 1979 aquatic plant survey was made only a few days after the dredging was completed. Thus there had been little opportunity for new plants to be established in the southern half of the dredged area. Dates of actual plant surveys are:

July 14 and 15, 1977,
August 15, 1978,
September 10 and 12, 1979.

Prior to dredging, water milfoil was spreading in the main part of the lake but was decreasing in the major coves due to competition with coontail and water lilies, which were both increasing their coverage. Figure 22 shows that water milfoil repopulated the earliest dredged areas with most of repopulation by drifting and rerooting of long water milfoil stems cut loose by the dredge. The population of these drifting plants was so severe in areas immediately adjacent of the dredged areas that a harvester was brought in to prevent the drifting water milfoil plants from becoming established. It should be noted that complaints about drifting and rerooting water milfoil plants occurred in areas distant from the dredge operation and clean up may be required in these areas in the future.

Table 24.

Common and Latin Names of Aquatic Plants in Morses Pond

Arrow Arum - *Peltandra virginica* (L.) Kunth.
Arrow-head - *Sagittaria latifolia* Willd.
Bladderwort - *Ultricularia minor* L. and *U. vulgaris* L.
Bur-reed - *Sparganium* sp(p).
Buttonbush - *Cephalanthus occidentalis* L.
Cattail - *Typha latifolia* L.
Coontail - *Ceratophyllum demersum* L.
Duckweed - *Lemna minor* L., *Spirodela polyrhiza* L., *Wolffia* [*punctata* Griseb.]
Elodea - *Elodea* sp.
Flatstem Pondweed - *Potamogeton zosteriformis* Fernald
Floating-heart - *Numphoides cordatum* (Ell.) Fernald
Floating Pondweed - *Potamogeton natans* L.
Nightshade - *Solanum dulcamera* L.
Periphyton - *Schizogonium* sp.
Pickerelweed, emergent form - *Pontederia cordata* L.
Pickerelweed, submerged form - *Pontederia cordata* L. forma [*taenia* Fassett.]
Purple Loosestrife - *Lythrum salicaria* L.
Quillwort - *Isoetes* sp(p).
Robbins' Pondweed - *Potamogeton robbinsii* Oakes
Sedge - *Cyperaceae* (Sedge Family)
Slender Arrow-head - *Sagittaria graminea* Michx.
Slender Pondweed - *Potamogeton pusillus* L.
Smartweed - *Polygonum* sp.
Spatterdock - *Nuphar variegatum* Engelm.
Swamp Loosestrife - *Decodon verticillatus* (L.) Ell.
Sweet Gale - *Myrica gale* L.
Variable Pondweed - *Potamogeton gramineus* L.
Water Milfoil - *Myriophyllum heterophyllum* Michx.
White Water Lily - *Nymphaea odorata* Ait.

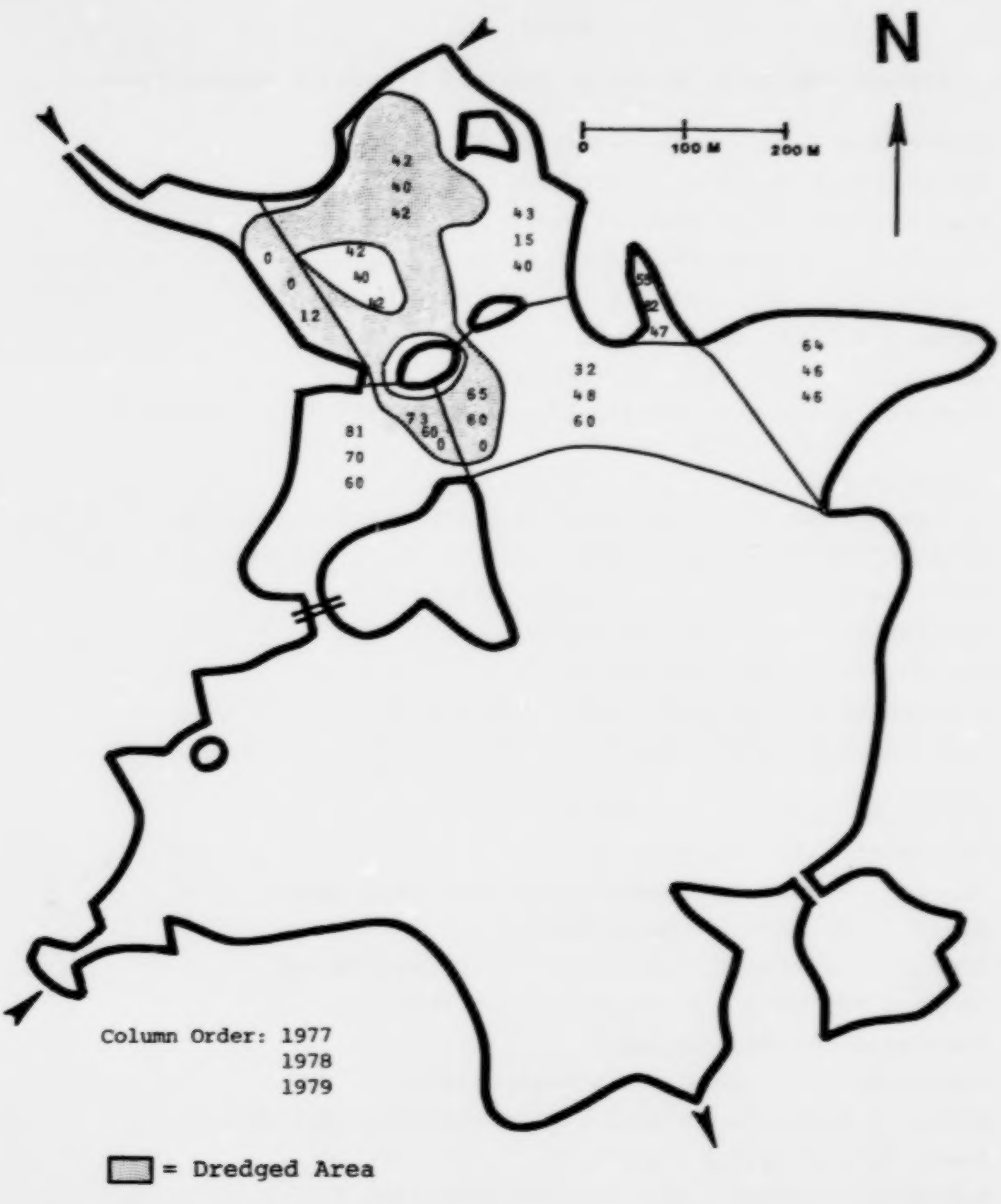
N
0
100 M
200 M
42
40
42
43
15
40
0
0
12
42
40
42
55
22
47
64
46
46
32
48
60
65
60
0
73
60
0
81
70
60
Column Order: 1977
1978
1979
▨ = Dredged Area

Figure 22. Percent Coverage of Water Milfoil.

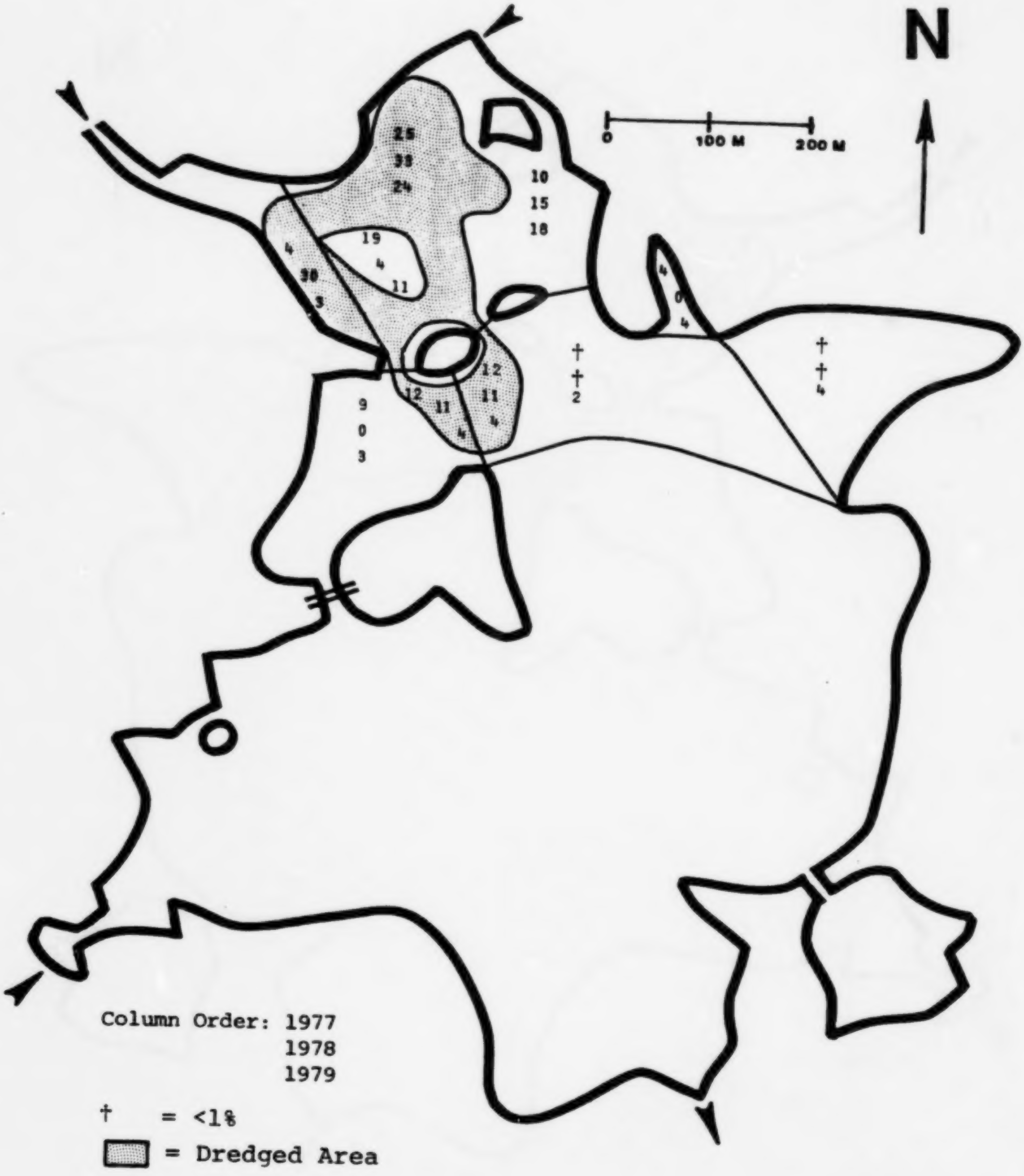
N
0
100 M
200 M
25
33
24
10
15
18
4
30
3
19
4
11
4
0
4
†
†
2
†
†
4
12
11
4
12
11
4
9
0
3
Column Order: 1977
1978
1979
† = <1%
▨ = Dredged Area

Figure 23. Percent Coverage of Coontail.

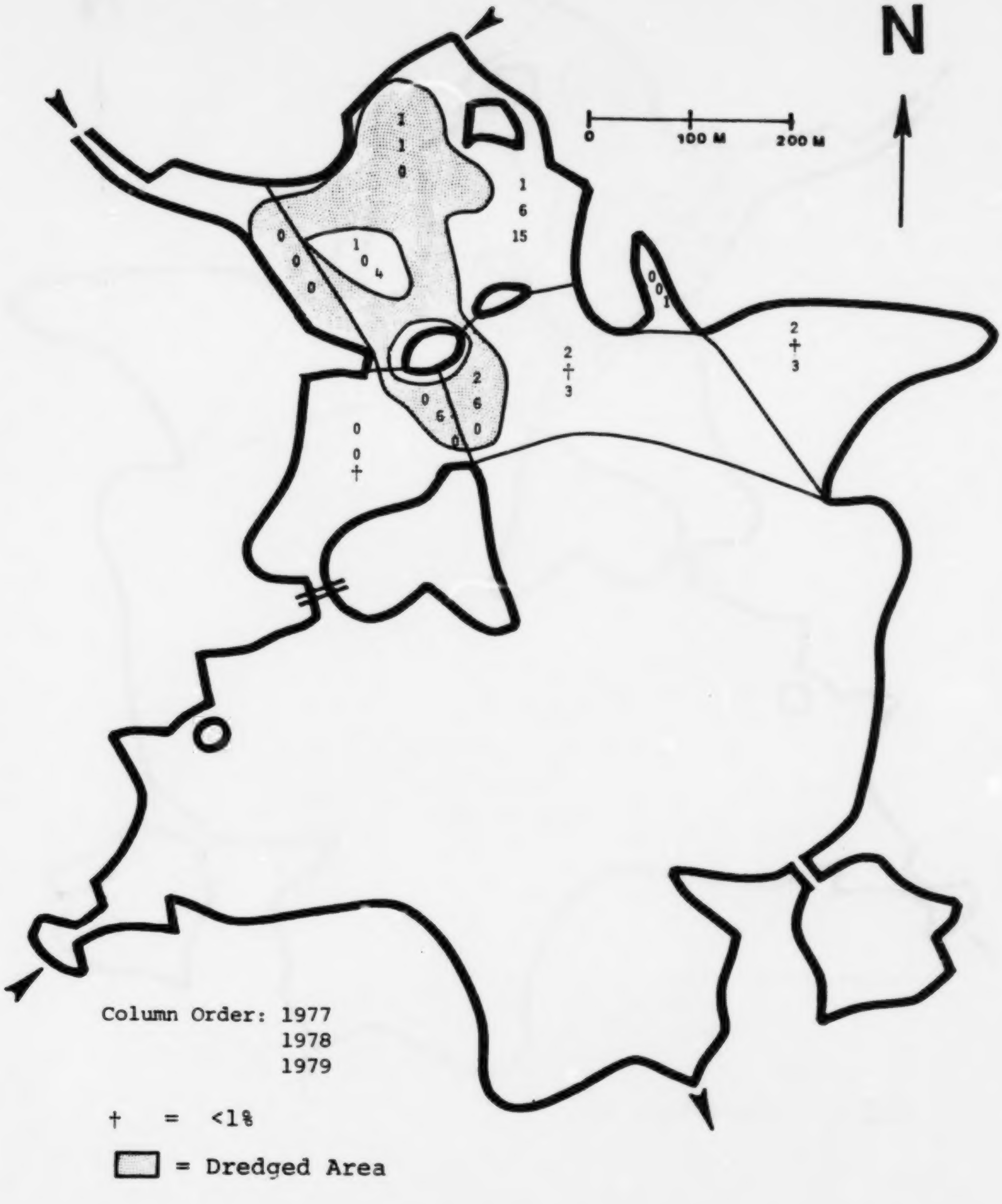
N
0
100 M
200 M
1 1 0
1 6 15
0 0 0
1 0 4
0 0 1
2 † 3
2 † 3
2 6 0
0 6 0
0 0 †
Column Order: 1977
1978
1979
† = <1%
▨ = Dredged Area

Figure 24. Percent Coverage of Robbins' Pondweed.

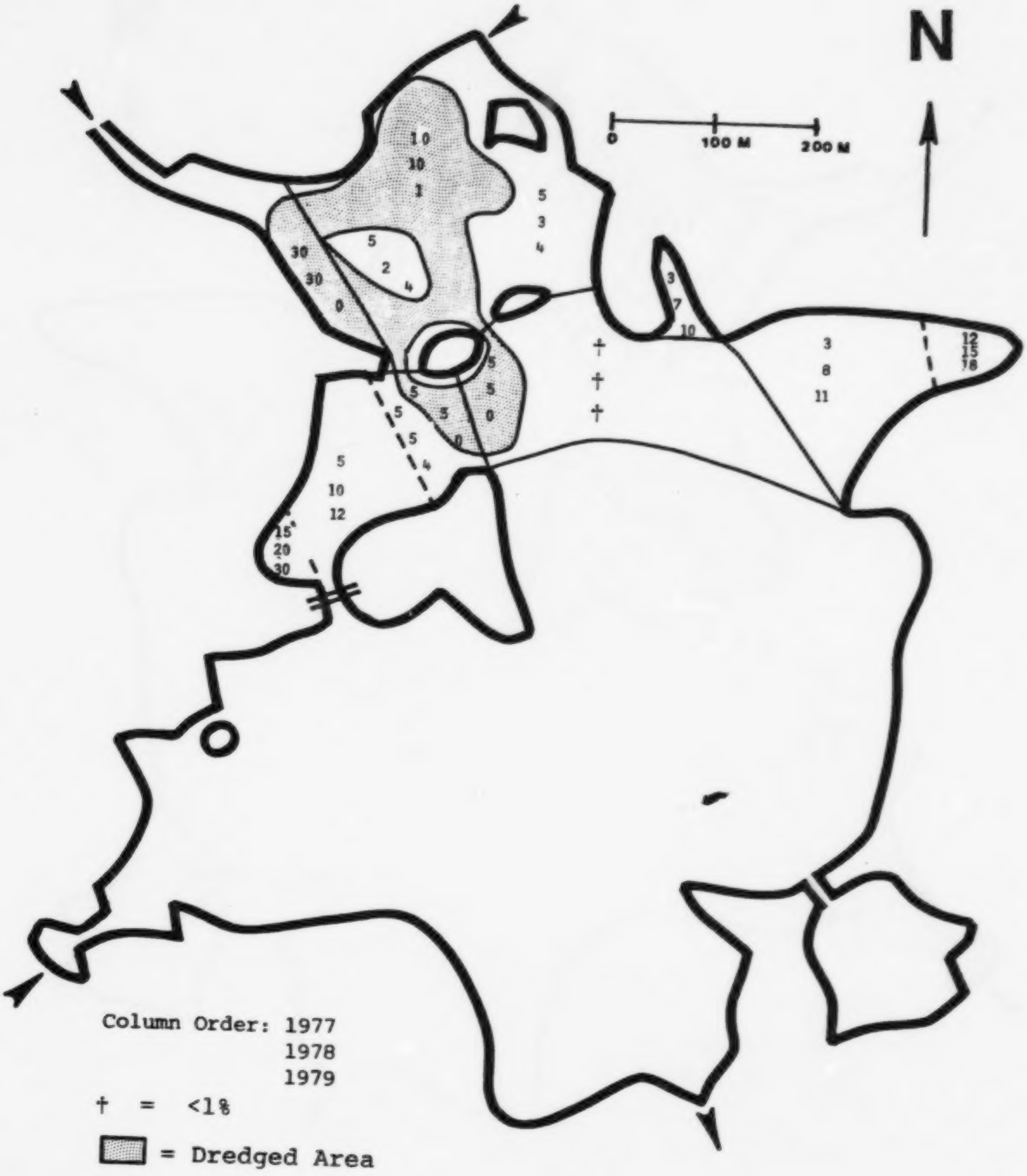
N
0
100 M
200 M
10
10
1
5
3
4
30
30
0
5
2
4
3
7
10
†
†
†
3
8
11
12
15
18
5
5
0
5
5
5
0
5
5
4
5
10
12
15
20
30
Column Order: 1977
1978
1979
† = <1%
▨ = Dredged Area

Figure 25. Percent Coverage of Spatterdock and White Water Lilies.

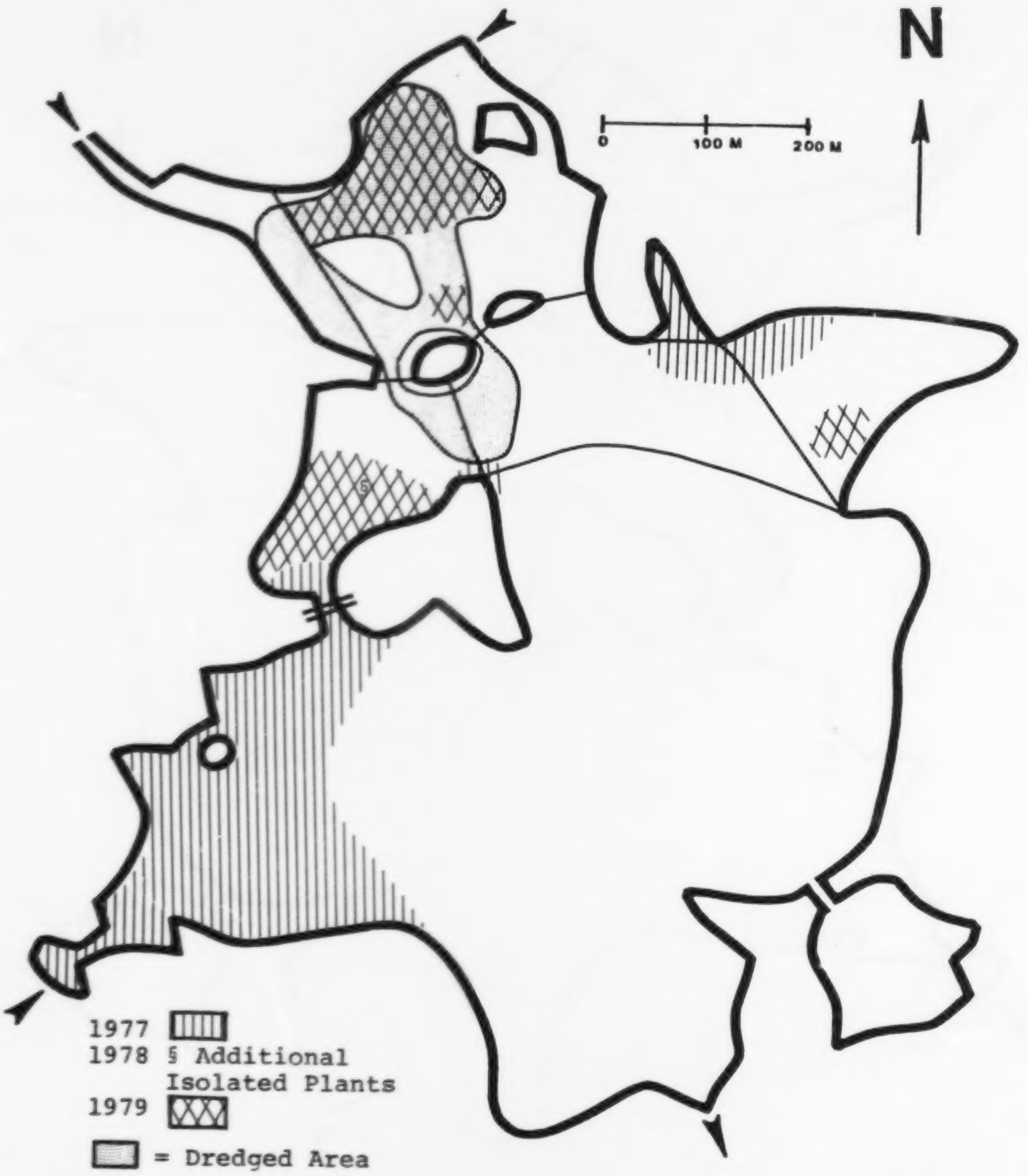
N
0
100 M
200 M
§
1977 ▥
1978 § Additional Isolated Plants
1979 ▦
▨ = Dredged Area

Figure 26. Distribution of Slender Arrow-head, 1977 - 1979.

The coontail was generally observed to be expanding in Morses Pond from 1975 to the present. The plant is expanding in terms of areal extent as well as present coverage as shown in Figure 23. The dredging did depress the coontail population but re-establishment of coontail seemed faster than water milfoil in the most recently dredged areas. It will be interesting to observe if coontail can out-compete water milfoil in the long run in the dredged areas.

Robbins' pondweed was also generally observed to be increasing in Morses Pond prior to the dredging. This plant was eliminated completely in dredged areas as shown in Figure 24, but it continues to expand its coverage in other areas of the lake. As a low profile aquatic plant that does not interfere with boating, this plant is recommended for post-dredging plantings in areas scheduled to be dredged.

Concerning water lilies, both the spatterdock (yellow water lily) and white water lilies are covered in this discussion. These plants were generally expanding in Morses Pond prior to dredging and in some areas the water lilies were quite dense. Figure 25 shows the water lily coverage but does not indicate the dense patches that account for much of the total coverage.

The water lilies were totally removed in the dredged areas. The areas that were dredged earliest in the program did have small seedlings of the spatterdock evident. These seedlings represent one of the two plants that appeared from seed in the post-dredging phase. No seedlings of the white water lily were observed.

The dredging impact on water lilies did have one major side effect. The rhizones of these plants, particularly of the spatterdock, drifted about the pond in large numbers. Numerous complaints were received and a two-man crew was eventually assigned to clean the pond of these drifting rhizomes. As far as is known, none of these drifting rhizomes became re-established although the drifting plants were observed to attempt regrowth of leaves while drifting.

Slender arrow-head (Sagittaria graminea) is the last major submergent plant to be discussed. It is important because it is another low profile plant that seems to be suitable for post-dredging plantings. When established, this plant frequently reaches 100% coverage in an area. For a low profile plant, this is considered quite desirable. Prior to dredging, this plant covered about 30% of the large cove in the southwest part of the main body of the lake. It was observed only as a few isolated plants in 1977 and 1978 in other areas of the lake. However, in 1979 the plants increased their areal coverage and a significant population was observed in the areas that were dredged in late 1978. Figure 26 shows the changing extent of these plants from 1977 to 1979. Since the dredge did not work in any areas where the plant existed previously, it can be concluded that the presence of this plant in dredged areas was from seeds that were buried in the mud. The resulting coverage was up to 15% in some areas.

The general impact of dredging on emergent plants was almost total removal. Buttonbush was totally removed from dredged areas. Ony one smartweed plant was observed to have escaped the dredge. A few cattails escaped the dredge and had drifted into shore at various locations around the lake. Most of these were removed by the town clean-up crew. Sedge removal by the dredge was quite complete. Not enough swamp loosestrife was dredged to allow any conclusion as to removal efficiency.

The one emergent plant that did clearly escape the dredge in significant amounts was arrow arum. This plant was observed drifting around the lake in large numbers during the dredging operation. Complaints were common about these large drifting plant masses. Even after a considerable effort by the town crew, there were still numerous smaller drifting plants observed throughout the pond during the post-dredging survey.

To summarize the impacts of dredging on the aquatic plant community:

1- water milfoil (as drifting plants) rerooted in the dredged area and coontail also repopulated the dredged areas.

2- water milfoil also drifted into undredged areas and thus increased water milfoil coverage especially in those areas nearest the dredging site;

3- seedlings of spatterdock and slender arrow-head appeared in the dredged areas with old slender arrow-head seeds being derived from the muds and not from an existing population;

4- drifting rhizomes of spatterdock and drifting arrow arum plants were so extensive that a work crew had to be assigned to keep these drifting plants under control; and

5- a harvester was used after the dredging had ceased, to remove drifting water milfoil before it rerooted in undredged areas.

Given the natural changes that are continually occurring in aquatic plant distributions in some lakes, it is difficult to assign any impacts from the chemical treatment program. The only item postulated for impact on the macrophytes is their possible increase in areal coverage at the expense of periphyton due to increased water clarity.

7.0 DREDGING

Major dredging programs for lake restoration are still an uncommon occurrence in New England. Most dredging in New England has been confined to small projects for creating ponds a few acres in size, or larger projects involving river or harbor maintenance in coastal areas. Thus there will be many towns with an interest in the practical problems associated with dredging in recreational lakes or dredging in urbanized areas.

7.1 Operational Problems

The first problem involved with this dredging program was the location of the spoils area. There was an abandoned gravel pit adjacent to the lake, but it was within 400 feet of Wellesley's main water supply wells. Given that nitrates and ammonia could leach from the spoils area, it was decided that the existence of the town wells was a knock-out factor for this site.

Four other sites were considered. One site was in a cut made by an old aqueduct. In considering this site, it was noted that a sanitary sewer trunk line ran in the aqueduct cut and that leakage into the sewer or the aqueduct itself could result in serious problems. Thus the site was dropped from further consideration.

Two other sites were located on vacant land owned by Wellesley College. One site was quite extensive. However, the topography would have required excessive earth moving to generate a large enough storage volume for dredging. Thus this site was also eliminated. The second site on Wellesley College grounds was an old abandoned gravel pit downstream from Morses Pond but above Lake Waban, which also lies largely on Wellesley College land. This became the disposal site.

The last remaining site was in a seldom used sports field above Morses Pond in the Town of Natick. Some officials in Natick encouraged the use of this site because they also hoped to eventually use it for dredging of Jennings Pond, which lies just above Morses Pond. However, the Town of Wellesley decided that the problems of crossing the town line were such that this latter area could be considered only as a last resort. Since the working relationship between the Wellesley Department of Public Works and Wellesley College was so good, the major focus became the abandoned gravel pit on Wellesley College land. Agreement was eventually reached with Wellesley College and the Natick site was dropped from consideration.

The spoils area on the Wellesley College site had a final design large enough for storing 36,700 cubic meters (48,000 cubic yards) of spoils. Due to anticipated compaction during drying periods, it was hoped that the volume actually dredged could be in excess of the storage capacity of the spoils area. In addition, the sands and gravel on this site were of sufficient quality and quantity that a containment area could be constructed without bringing in materials from outside sources. The actual site was level on one side and was flanked by an esker on the other side. To make this site a true containment area, sand and gravel was taken from below existing grade and a berm was constructed on the low side. The resulting depth in the spoils area was 7 meters (23 feet) even though the outside of the berm stood only 4.3 meters (14 feet) above the existing grade.

The shape of the spoils area was somewhat like a long-necked gourd. There was a long narrow neck about 18 meters (60 feet) wide and some 90 meters (300 feet) long before the spoils area opened into a wider area. The discharge pipe was placed so that all the spoils arrived at the end of the neck furthest from the main part of the spoils area. This site is shown in Figure 27 and a typical cross-section is shown in Figure 28. Besides raw containment of spoils, some provision had to be made for control of turbid water once the spoil area was full. It should be stressed that the water:mud ratio for a hydraulic dredge is about 6:1 during pumping, so large volumes of potential effluent have to be considered. Only two options were considered for this site. They were (1) split the spoils area into two settling basins for alternate use and (2) use a sand filter. Due to the constraint on land area, the former was rejected due to the significant loss in spoils area volume caused by the separating berm.

Thus a small sand filter was constructed with its containment berms. The original plan for this sand filter called for an area of 18 x 45 meters (60 x 150 feet). This sand filter was proposed for clarification of any overflow from the spoils area before discharging the elutriate into the brook draining into Lake Waban. This brook contained all the water normally draining from Morses Pond.

The next set of problems arose as the permitting process began. Permits were required from:

- The Wellesley Conservation Commission which acts as an agent for the state in administering and enforcing the Massachusetts Wetlands Protection Act;
- Massachusetts Division of Water Pollution Control (1978) Water Quality Permit and the Massachusetts Dept. of Public Works, Chapter 91 review;
- Department of the Army, Corps of Engineers Permit (Dept. of Defense, 1975); and

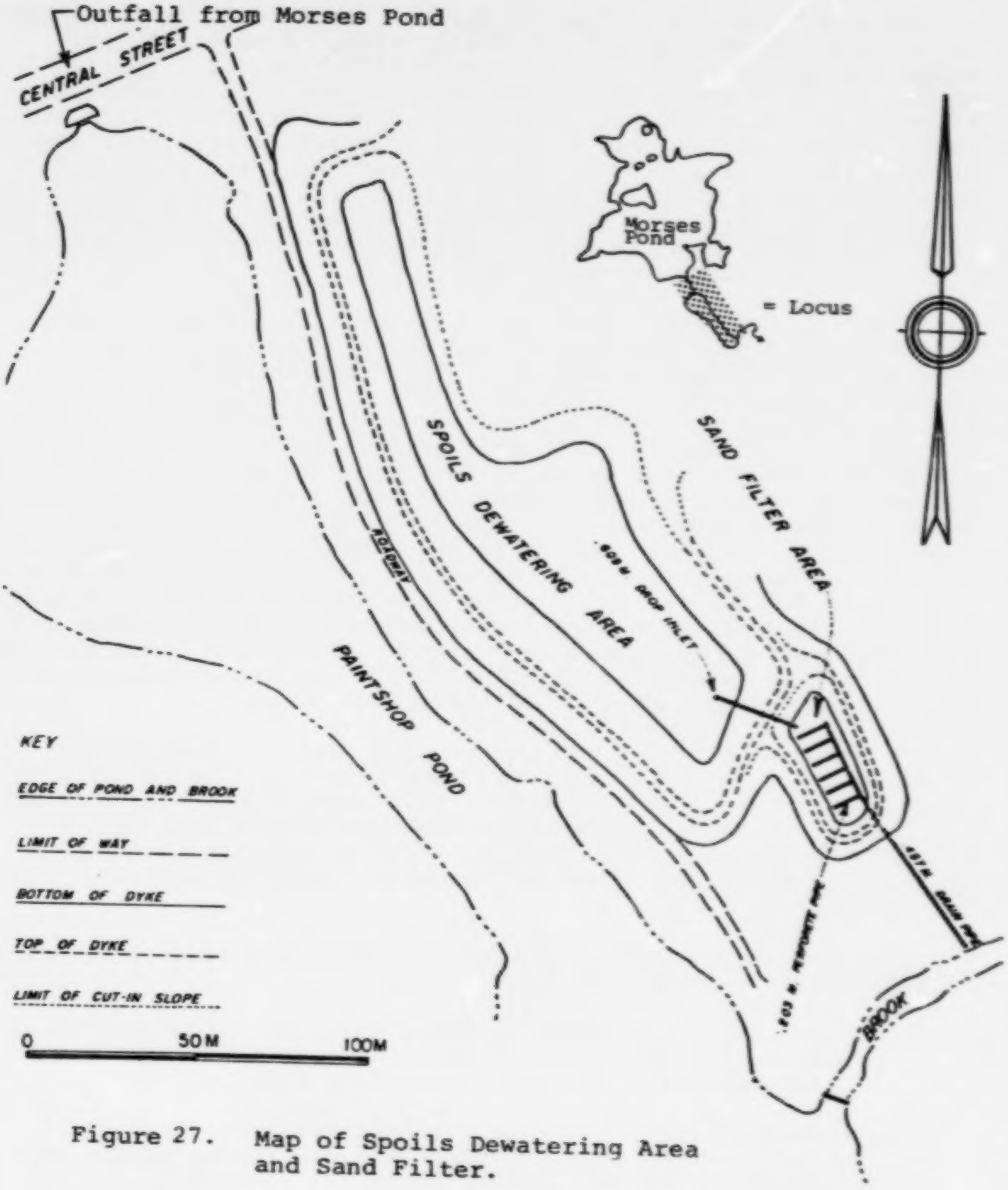
Outfall from Morses Pond
CENTRAL STREET
Morses Pond
= Locus
SPOILS DEWATERING AREA
SAND FILTER AREA
ROADWAY
PAINTSHOP POND
.608 M DROP INLET
401 M DRAIN PIPE
.603 M PERFORATE PIPE
BROOK
KEY
EDGE OF POND AND BROOK
LIMIT OF WAY
BOTTOM OF DYKE
TOP OF DYKE
LIMIT OF CUT-IN SLOPE
0
50 M
100M

Figure 27. Map of Spoils Dewatering Area and Sand Filter.

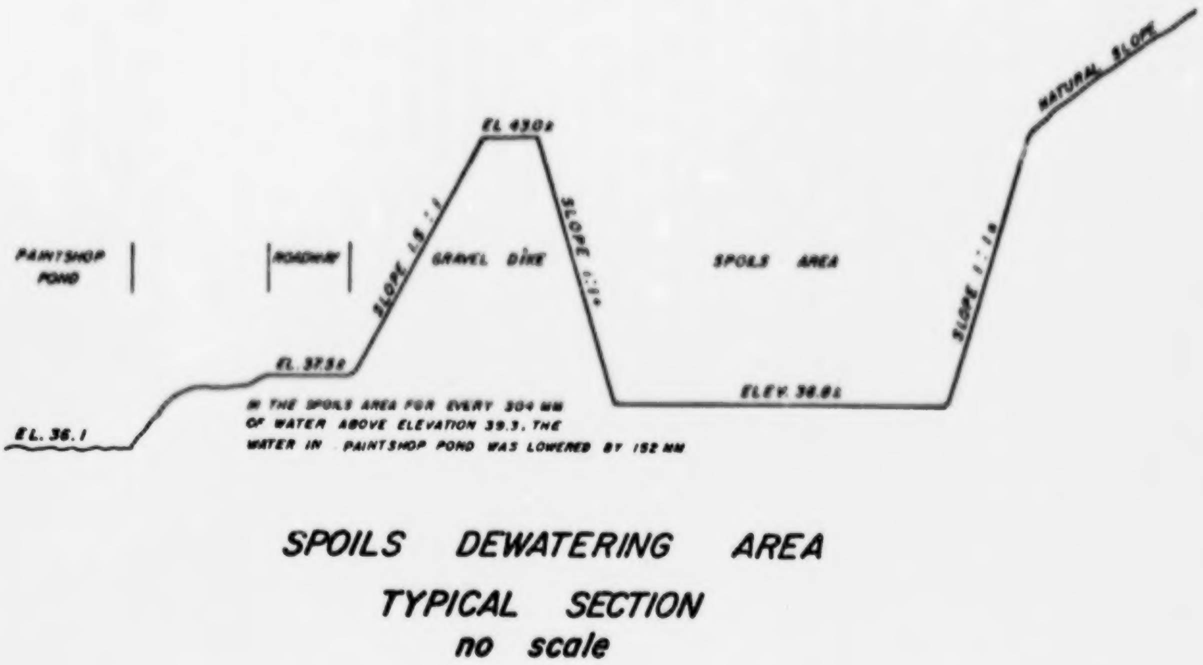
PAINTSHOP POND
ROADWAY
GRAVEL DIKE
SPOILS AREA
NATURAL SLOPE
SLOPE 1.5:1
SLOPE 1:1±
SLOPE 1:1.6
EL. 36.1
EL. 37.5±
EL 43.0±
ELEV. 38.8±
IN THE SPOILS AREA FOR EVERY 304 MM OF WATER ABOVE ELEVATION 39.3, THE WATER IN PAINTSHOP POND WAS LOWERED BY 152 MM
SPOILS DEWATERING AREA
TYPICAL SECTION
no scale

Figure 28. Typical Cross-Section of the Spoils Dewatering Area.

- Wellesley College which had the final say as the land owners.

The college used the staff of the Biology Department as its technical advisors. The first specific problem that arose in getting all the permits and permissions was that every agency wanted different tests. The state was the exception, being satisfied with the Corps of Engineers requirements. All the additional testing took time and money.

The second specific problem involved satisfying the Wellesley Conservation Commission that the slopes on the berm were adequate. The Conservation Commission was concerned with the structural integrity of the slopes. Thus the design was adjusted to meet state standards for embankment construction and this satisfied the Conservation Commission. The final slopes actually constructed were about 1.5 to 1. Some erosion did occur on these slopes and mulching should be considered for such slopes if any similar project is expected to have a duration of more than one or two seasons.

The next problems that developed were the unexpected discovery of material buried on the dewatering site. The spoils area was sited where a nearby, but long gone, paintshop used to dispose of its paint wastes. Green and yellow paint contaminated soils were found in quantity and the question immediately arose about pollution hazards due to the paint. Soil samples were taken and tested for heavy metal release during water contact. Tests included zinc, nickel, copper, lead, arsenic, cadmium, cobalt, chromium, mercury, barium, nitrate, vanadium, selenium, oil and grease, silver, beryllium, and hydrocarbons as mineral spirits. The test results showed that nitrate, chromium, lead and cadmium all violated permissible criteria for drinking water as established by the Federal Water Pollution Control Administration (1968). The results of this testing is presented in Table 25. Given these test results, it was decided that no paint contaminated soil would be allowed in the berm nor below the spoils area. Thus these contaminated soils were stockpiled on site for ultimate disposal at a later date.

The second buried material was a collection of tree stumps from the 1938 hurricane. Since these stumps were unsuitable for inclusion in the berm, they had to be removed and stockpiled outside the spoils area. These two discoveries added about $5,000 to the cost of the spoils area.

The next problem arose about midway through the containment area construction. Wellesley College representatives requested that the spoils area not cut so deeply into the esker. "Saving trees" appeared to have been part of the reason for the request. The resulting "on site restriction" resulted in a loss of 4600 cubic

Table 25. Chemical Releases From Paint Contaminated Soils

Potential Contaminant (mg/l unless indicated)	Distilled Water Purge 1:1 by wt	Standard Elutriate Test	Natural Site Water
Zinc	0.15	0.04	<0.02
Nickel	0.18	0.11	<0.02
Copper	0.12	0.02	<0.02
Lead	0.30	0.14	<0.02
Mercury (ppb)	<0.5	<0.5	<0.5
Cadmium	0.04	0.03	<0.02
Cobalt	0.11	0.06	<0.02
Arsenic	0.013	0.020	<0.005
Barium	<0.05	<0.05	<0.05
Total Chromium	265	156	0.08
Nitrate-Nitrogen	58.5	35.5	0.10
Vanadium	<0.05	<0.05	<0.05
Selenium	<0.02	<0.02	<0.02
Oil and Grease	NA	1.1	1.5
Silver	<0.02	<0.02	<0.02
Hydrocarbons (Min. Spirits)	<2	<2	<2
Beryllium	<0.02	<0.02	<0.02

meters, (6000 cubic yards) or 13% of the storage volume and about 50% loss of sand filter area. These losses limited the dredging and added extra cost to the program. This added cost resulted from having to move materials out of the spoils area to make up for some of the lost spoils area. The volume moved during an interuption in dredging was 3800 cubic meters (5000 cubic yards) at a cost of $10,900.

Actual dredging began in November of 1978 and continued until ice forced the dredge off the lake in the third week in December. About 20,000 cubic yards of material was dredged before the winter shutdown. During this first round of dredging, the first sand filter problems appeared. The sand filter problems are discussed below.

A typical sand filter design calls for the underdrain pipe to be placed in a trench surrounded by 2.5 to 5.0 cm (1 to 2 inch) of crushed stone, overlain by 0.6 to 2.5 cm (0.25 to 1 inch) of crushed stone, overlain by stone less than 0.6 cm (0.25 inch), and finally a cover of 0.6 m (2 feet) of sand. Unfortunately, intermediate grade stone was reported as not being immediately available so the 2 intermediate layers were ommited during initial construction of the sand filter. Also, the coarse layer of stone appeared to be larger than 2 inches. The initial sand layer used was sand from the site and it did not meet the specifications for a filter sand. Finally, the underdrain ends were left open and there was only a double row of holes along the top of the underdrain pipe. The result was that the sand filter failed several times during the Fall dredging period. Release of turbid water into Lake Waban was the result of these failures and this turbidity was noticed only where the stream entered the lake.

The first failure was due to lack of covering at the ends of the pipes. The rocks moved into the pipes, the sand washed through the rocks, and the turbid dischare water washed directly into the underdrains without filtration. The ends of the pipes were then sealed with wire mesh and the rocks and sand replaced.

The next failure occurred as (1) the rush of water from the pipe emptying into the sand filter washed away the sand from the nearest underdrain, and (2) the sand directly over the underdrains slowly washed through the coarse rock. The result was that the underdrain trenches were easy to locate due to the sand washthrough and essentially no filtration occurred. At the end of the fall dredging the consensus was that the sand filter clearly needed upgrading. At this stage the Corps of Engineers altered their previous decision and now required that the town file for a discharge permit. In addition, the Mass. Division of Water Pollution Control increased their monitoring requirement. Tables 26 and 27 present the performance results in the Fall of 1978.

Table 26. Chemical Sampling of Filter Bed Inflow and Outflow. November 21, 1978. All units in mg/l. except as noted.

	Filter In	Filter Out
Total Phosphorus Unfiltered	0.17	0.18
Total Phosphorus Filtered	0.01	0.01
Total Ortho Phosphate	<0.01	<0.01
Total Kjeldahl Nitrogen Unfiltered	2.0	2.0
Total Kjeldahl Nitrogen Filtered	1.0	1.4
Ammonia Nitrogen	0.62	0.60
Nitrate Nitrogen	0.23	0.05
Nitrite Nitrogen	0.007	0.007
Total Iron Unfiltered	2.5	2.4
Total Iron Filtered	0.05	0.05
Total Alkalinity Unfiltered	19.3	17.3
Total Alkalinity Filtered	18.2	16.9
Arsenic	0.026	0.013
Color (αPt-Co Std)	>500.	>500.
Turbidity (FTU)	175.	145.
Turdidity after one hour	170.	140.
Turbidity after six days	12.	38.

Note that where neither filtered or unfiltered is noted the parameter is soluble and filtration would not affect the results.

Table 27. Testing Results of Spoils Area Influent and Effluent, 13 December 1978. Five sites were tested: (1) into the sand filter, (2) out of the sand filter, (3) the receiving stream above the sand filter discharge, (4) the receiving stream below the discharge, and (5) the receiving stream after it had flowed through a small wetland but before it reached Lake Waban. All units are in mg/l except as noted. Turbid samples were allowed to stand for one hour before chemical processing.

	Inflow	Outflow	Upstream	Downstream	Below Wetland
Total Phosphorus Unfiltered	0.24	0.27	0.02	0.10	0.10
Total Phosphorus Filtered	0.03	0.06	0.02	0.02	0.03
Total Ortho Phosphate	0.01	0.01	0.02	0.01	0.01
Total Kjeldahl Nitrogen Unfiltered	4.5	4.4	0.40	1.2	0.79
Total Kjeldahl Nitrogen Filtered	1.1	1.3	0.40	0.50	0.45
Ammonia Nitrogen	0.60	0.60	0.07	0.19	0.19
Nitrate Nitrogen	0.50	0.52	0.11	0.16	0.17
Total Iron Unfiltered	4.2	3.8	0.32	1.3	1.2
Total Iron Filtered	0.04	0.14	0.32	0.13	0.04
Total Alkalinity Filtered	16.7	16.7	31.5	26.8	28.6
Color (αPt-Co Std)	500+	500+	60	500+	495
Turbidity (FTU)	500+	500+	0	108	85
Turbidity After One Hour	500+	500+	0	50	88

Before the spring round of dredging began, it was evident that the dredging would continue well into the 1979 recreation season. This required some revision of the dredging pipe locations since the pipe ran right across the town's only swimming beach. To keep the beach in use, it was decided to bury the dredge pipe under the beach. This was done and no problems occurred at the beach while the pipe was in operation. The only problem that did develop was due to the gravel which lay under the beach sand. Due to pipe burial, clays washed out of the exposed gravel and these fines settled in the shallow areas. Once the swimming activity began, these clays were resuspended in the water and visibility in the shallow areas was reduced to about five feet while visibility in the deep areas was unaffected. As the recreation season progressed, the currents slowly washed the clay out of the recreation area and visibility improved.

The sand filter was also up-graded before the dredge was turned on. Unfortunately, more problems developed with the sand filter. The problems with the sand filter were due to (1) use of only 0.3 m (1 foot) of sand instead of 0.6 m, and (2) continued wash-through of sand even though some intermediate size stone was added. The dredging was stopped and the sand filter again rebuilt using a new sand and a full 0.6 m (2 feet) layer of sand. The resulting effluent from the sand filter was of excellent quality, but the new sand was not of filter grade quality and thus it plugged up and drained far too slowly for economical dredging. The dredge operator threatened to claim the job if the sand filter operation wasn't improved to allow faster dredging.

Thus the sand filter was replaced again and this time a soil retention fabric was used with a thin layer of washed concrete sand. The fabric soon plugged up and the drainage was again too slow. At this stage, consultants experienced in sand filter design were called in and the problem was discussed with the Corps of Engineers personnel. After reviewing the problem, it was the consensus that:

- the sand filter was too small and that more area than was available would be needed for a working field of sand filters;

- the washed concrete sand wasn't good enough but that a sewage treatment sand was available from New Jersey; and

- since there was no guarantee that this new sand would do the job, and because of high costs, the concept of importing special sand was dropped.

The conclusion was to step to batch treatment of the spoils area

Table 28. Sand Filter Performance with Two Feet of Sand and Performance with Batch Treatments of Alum. All units in mg/l except as noted.

	Sand Filter with Two Feet of Sand		Alum Batch Treatments					
Date - 1979	6/6	6/6	6/28	7/11	7/26	8/10	8/24	9/6
Sample	In	Out	Out	Out	Out	Out	Out	Out
Total P	1.1	0.06	0.06	0.03	0.06	0.05	0.04	0.05
NH_3-N	1.3	0.45	1.2	0.92	0.90	1.44	1.40	2.10
NO_3-N	0.38	0.65	0.20	0.03	0.10	0.05	0.10	0.03
Total Fe	10.5	0.24	1.0	1.8	3.4	2.2	5.6	3.7
Color (αPt-Co Std)	340	50	0	0	0	0	0	0
Turbidity (FTU)	>500	0	20	2	20	18	15	2
Suspended Solids 30 Minutes	-	-	<1	<1	<1	<1	<1	<1

with alum. The performance of the sand filter with 2 feet of sand is shown in Table 28. A cross-section of the functional sand filter is shown in Figure 29.

Before making the change to batch treatment by alum, it was necessary to alter the outlet standpipe in the spoils area so that the spoils area could be filled with mud and water and the water released. This alteration included increasing the height of the standpipe and installation of a series of drainage gates at different elevations along the standpipe. In addition, the sand filter was altered once more.

The final operation in the spoils area was as follows.

1- The dredge operated until the spoils area reached its allowable level. The ports on the standpipe allowed only a small amount of leakage.

2- Once the spoils area was full, a liquid alum treatment at approximately 50 mg/l was applied. The town tried using powdered alum but the mixing process placed too costly a demand on manpower and the results were inconsistent.

3- The water in the spoils area generally cleared overnight following an alum treatment.

4- The gates on the standpipe were opened and the water was released into the modified sand filter.

5- Once empty of water, the dredging began again.

The sand filter, as redesigned, had a dual function. It functioned as a sand filter to clean up the leakage during dredging and it functioned as a rapid by-pass filter during the major drainage events. This dual functioning was achieved as follows.

The sand filter was divided into two zones. The zone nearest the delivery pipe had only coarse stone covering the underdrains. Since the alum treatment left the water with near zero turbidity, no filtering for turbidity control was necessary. The second zone of the sand filter was sand over fabric over coarse stone. This area was furthest from the delivery pipe. When turbid dredge water was leaking through the standpipe, it spilled from the delivery pipe into a corregated metal half-pipe. This half-pipe served as a channel to carry the small volume of leaking water past the coarse stone area into the sand filter area. In this way, the sand filter only operated on the trickle phase. When clean water entered the sand filter, it passed through the rocks and essentially by-passed the sand filter even though the sand

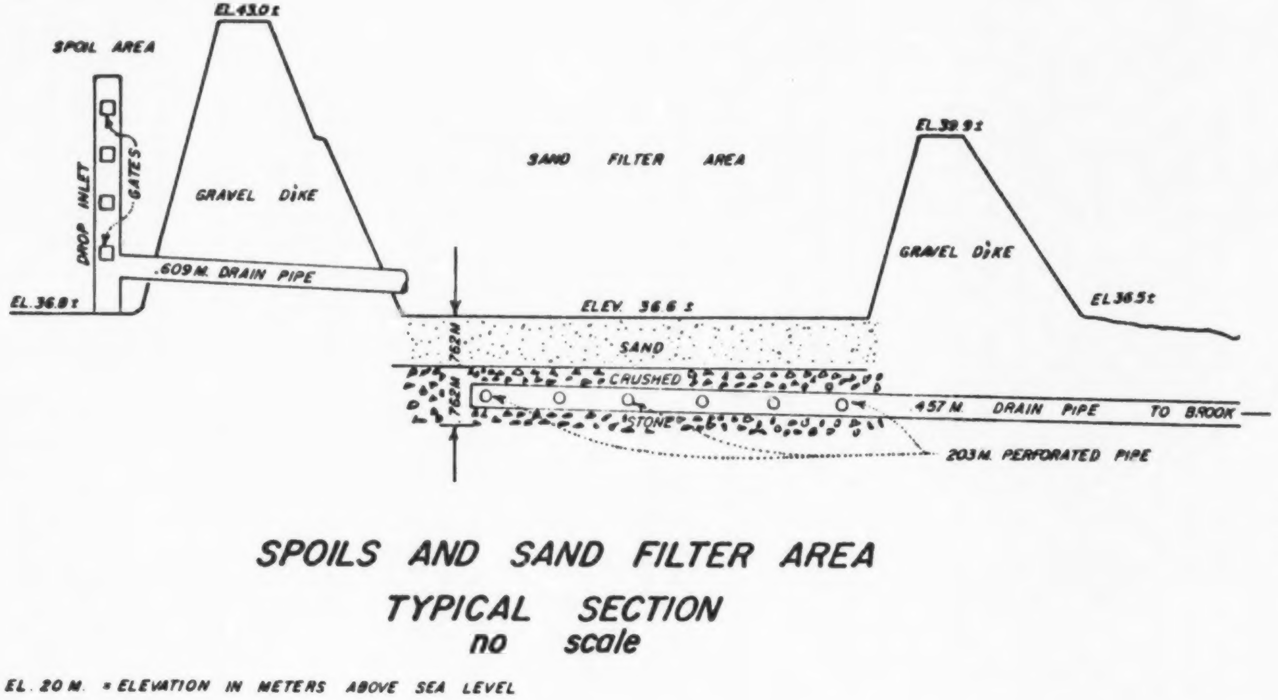
SPOIL AREA
EL.43.0±
DROP INLET
GATES
GRAVEL DIKE
.609M. DRAIN PIPE
EL.36.8±
SAND FILTER AREA
EL.39.9±
GRAVEL DIKE
EL.36.5±
ELEV. 36.6±
.762M
.762M
SAND
CRUSHED
STONE
.457M. DRAIN PIPE
TO BROOK
.203M. PERFORATED PIPE
SPOILS AND SAND FILTER AREA
TYPICAL SECTION
no scale
EL. 20 M. = ELEVATION IN METERS ABOVE SEA LEVEL

Figure 29. Typical Cross-Section of the Sand Filter. See Figure 27. for plan of the sand filter.

filter area was flooded too. Table 28 presents the quality of the alum treated effluent.

This process continued until the spoils area was essentially full of sediment. It should be noted that the accumulation of sediment in the spoils area had the effect of continually reducing the amount of dredging that occurred before the spoils area was full of turbid water. At the end of the dredging, the dredge was only operating for a few hours before the spoils area was full.

7.2 Dredging Costs

The first consideration in cost evaluation of a dredging operation is the comparison between a large dredge versus a small dredge. The options the Department of Public Works had to consider were (1) purchase a small Mud-Cat type dredge and use town manpower, or (2) contract the operation to a firm with a larger cutter-head dredge. The second option was recommended for the following reasons.

1- There were areas of dense buttonbush that are just too difficult for a Mud-Cat type dredge to deal with. This was later confirmed by a canoe channel project in Boxford, Mass., where other equipment had to be brought in to remove the buttonbush.

2- The town wanted to get the dredging over with quickly because of recreational demands on the pond. It was estimated that more than one recreational season would be impacted if a small dredge were used.

3- The Board of Public Works suggested that the town should not get involved in performance of services that were commercially available. The reasoning here was that (a) the town should only supply services that cannot be provided elsewhere, and (b) the hidden cost of town overhead and pension liability reduced the apparent favorable costs of town performance.

4- Given the distances to the disposal area of 1100 m (3600 feet), if a small dredge were used, there would be the additional cost of town purchase or rental of dredge pipe and booster pump which would further reduce apparent savings on town perfomance. It should be noted that an extra booster pump is not required by a large dredge because of its inherent greater pumping capacity.

5- A Mud-Cat type dredge requires shore anchoring and a major portion of the shoreline was in private hands thus opening the door for shoreline damage suits.

Turning to the bid process for dredging, it soon became apparent that there was a large difference between the bid costs per cubic meter of dredging versus the total cost of the entire operation. The former just reflects the cost of running the dredge and this cost is usually so many dollars per unit volume of sediment moved. However, the real cost of dredging can only be defined when one includes all the associated costs of:

- mobilization and demobilization of the dredge;
- security;
- preparation of the spoils area;
- permit acquisition;
- effluent monitoring;
- work order changes; etc.

When the specifications were released for bidding in August 1978, there was only a 4% difference between high and low bidder for the total job. However, the bids were structured so differently for the various work elements in the total dredging job, that careful analysis was required in order to get the most mud moved for the limited dollars available. The major difference between the winner and losers of the bid was that the losers had very high front-end cost for launching and setting up the dredge and preparation of the spoils area. Then, the losers had a low per cubic meter cost component to make up for the large front-end cost. The problem the town faced in bid selection was that all the front-end costs were so high that the dollars available limited the dredging program. Thus the dredging contractor selection fell to the bidder with the lowest front-end cost but the highest per cubic meters component. When all the costs were figured in, the winner had the lowest total price per cubic meter. Table 29 summarizes the bid costs per 1978 for the first phase of the dredging contract.

Even before the dredging began, it was realized by the town that the earlier imposed dollar limit was not going to dredge enough of the lake to achieve the desired goals. Thus the Town Meeting appropriated more money and the Federal EPA matched the town appropriation to expand the scope to the dredging program. This was done to achieve the desired goal of "fill the spoils area once without paying for a second mobilization cost." Thus the size of the spoils area became the new limit on the project.

Before completing the analysis for the final dredging costs, it must be realized that the bid costs presented in Table 29 do not

TABLE 29. Dredging Bid Analysis. These bids refer to only the first phase of dredging and do not include extra work items. The cost of the second phase of dredging and extra work items altered the final costs.

Bidder Number	Cost per m^3 (yd^3)	Mobilization-Demobilization Cost	Disposal Area Cost	Cost/m^3(yd^3) for desired 58,100 m^3 (76,000 yd^3) Dredging	Cost/ m^3(yd^3) for realistic 22,175 m^3 (29,000 yd^3) Dredging
1*	$5.56 ($4.25)	$50,000.	$40,000.	$7.11 ($5.43)	$9.62 ($7.35)
1†	$5.01 ($3.83)	$50,000.	$40,000.	$6.56 ($5.01)	$9.07 ($6.93)
2	$4.03 ($3.08)	$136,000.	$43,000.	$7.11 ($5.44)	$12.10 ($9.25)
3	$3.60 ($2.75)	$150,000.	$66,000.	$7.31 ($5.59)	$13.34 ($10.20)

* Contractor suppies spoils area security.
† Town supplies spoils area security.

reflect all the actual costs incurred by the dredging project. As can be seen from Section 7.1, there were a number of items that added cost to the dredging. Section 7.1 items and approximate costs include:

- removal of buried stumps	$ 3,800.
- removal of spoils from spoils area	10,900.
- multiple reconstructions of sand filter	13,600.
- testing paint contaminated soils	1,100.
- testing for permitting agencies	3,300.

Items not discussed in Section 7.1 and their approximate costs were:

- fence the spoils area for security	$11,300.
- pre- and post-dredging surveys to calculate mud volumes	9,000.
- cost of alum plus manpower	8,500.
- extra work relative to operational problems and testing	18,000.
- monitoring	1,500.
- numerous small miscellaneous expenses	2,800.

If we subtract the research associated costs of this job from the total town + state + federal expenditures, the final cost of dredging becomes $488,000 for 41,478 cubic meters (54,248 cubic yards) of dredging. This includes both phases of dredging. In the final analysis, the cost of dredging became $11.77 per cubic meter or $9.00 per cubic yard. This does not include costs for final restoration in the spoils area. There is presently another dredging program on-going in Billerica, Massachusetts where the town purchased a Mud-Cat dredge. The comparative costs of use of this smaller dredge should be valuable once the Billerica project is completed.

The biological and chemical responses to dredging are defined in earlier sections of this report. The ultimate disposal for the dredging spoils will be determined by Wellesley College. Most likely, the spoils area will be graded into a playing field.

8.0 Why Lakes Become Nitrogen Limited

It is a well known phenomenon that as lakes become more nutrient rich, they often change their limiting nutrient from phosphorus to nitrogen. The data collected or reviewed for this report suggest some reasons why the limiting nutrient changes.

First, look at the N/P ratio for septic tank effluent. This ratio is about 3:8 and this value is of great concern for houses near a lake. In these houses, the small distance between the septic field and the lake imply that in a few years the soil adsorption capacity for phosphorus will be fully utilized. Once this phosphorus adsorption capacity is lost, then the N/P nutrient loading from nearby septic tanks will favor nitrogen limitation.

A second factor operating to drive a phosphorus limited lake into nitrogen limitation is metabolism by-product release from macrophytes. Based on evaluation of fluids from water lilies (see Section 5.2), the ratio for total N to total P averages 5.4 with biologically available forms averaged at 2.9. Both these ratios demonstrate that plants release phosphorus in excess of nitrogen, relative to plant growth needs. This again favors nitrogen limitation over phosphorus limitation.

Schroder's (1974) study of releases from emergent plants also points to a metabolism by-product release rate that favors nitrogen limitation. This is important because it shows that as emergent plants form fringing marshes and they begin to expand into a lake, this favors conversion to nitrogen limitation via internal nutrient loading.

A third factor favoring conversion to a nitrogen limited system is the nature of some kinds of periphyton as nutrient sinks. The average N/P ratio for the periphyton samples discussed in Section 6.2 was 47. This shows excess nitrogen storage over phosphorus storage and this storage phenomenon again favors nitrogen limitation in lakes.

A further factor affecting the total nutrient loading of lakes is hypolimnetic nutrient recycling. As part of a study of lakes in Berkshire County, Massachusetts, in 1976, there were 4 lakes that demonstrated summer nutrient releases at depth. In comparing nutrient concentrations in the surface versus concentrations at depth, the average N/P ratio for the 4 lakes was 7.8. This again favors phosphorus recycling over nitrogen recycling and represents one more loading factor that tends to drive a lake into nitrogen limitation.

Notice that all the items discussed above imply that it is the nature of nutrient sources and sinks relative to the nutrient needs of plants that force a lake into nitrogen limitation. What is now needed in the science of limnology is an accurate way to realistically quantify these internal nutrient loads. Vollenweider's (1975) curves can then be used for total nutrient loading rather than just loading from external sources. It has been our experience to date, that given reasonable estimates for internal nutrient loadings, that Vollenweider's (1975) curves more accurately reflect a lake's trophic status than mere calculations of external nutrient sources.

There is one final item that should be pointed out relative to the limiting nutrient issue. There are a number of individuals who believe that nitrogen deficiency in lakes is satisfied by nitrogen-fixation by blue-green algae. In studying the lakes of Berkshire County, in 1976, it was discovered that Lake Onota and Woods Pond, which were both strongly nitrogen limited, showed no evidence of nitrogen-fixing blue-green algae. Thus the mere fact of nitrogen limitation is not enough for internal correction via nitrogen-fixation. Given that nitrogen-fixation does not universally frustrate a nitrogen control strategy for lake management, and given the 5 years experience in blocking nitrogen-fixation in Morses Pond by control of iron as documented herein, and given that internal phosphorus sources may be large enough to frustrate a lake management program aimed solely as external phosphorus sources; it is clearly time for lake management specialist to evaluate both nitrogen and phosphorus control strategies for nitrogen limited lakes.

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Appendix A - "Algal Blooms - Possible Effects of Iron"

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Abstract:

Iron, in concentrations of 0.1-1.0 mg/l, causes a shift in the dominant type of algae grown in batch cultures from relatively unobjectionable greens to the scum-forming blue-greens, without causing a significant change in the total algal biomass. Results were not dependent on the manganese concentration (0-0.40 mg/l) of the phosphorus concentration (0.07-7.0 mg/l).

Perhaps the most widely publicized method of controlling excessive algal growth in a lake is by limiting an essential nutrient, such as the removal of phosphorus from sewage effluents and detergents. However, not all types of algae are equally troublesome in eutrophication problems. Blue-green algae, which form surface scums and cause odors, are very undesirable at typical algal bloom concentrations of 6-12 mg/l (dry weight) while the same amounts of green algae are not so objectionable. It is therefore important to understand the chemical and physical conditions that control the dominant algal type.

It is well known that certain factors, both natural and man caused, can increase the green to blue-green algal ratio (G/BG), without necessarily changing the total algal biomass. The diversion of domestic sewage effluent away from a lake can cause the G/BG to increase as does aeration, mixing, and upwelling. Symons (1969) and coworkers, Bernhardt (1967), Wirth et al. (1970), and others have documented the increase in the G/BG and the changes in water chemistry when small lakes and reservoirs are mixed mechanically or with compressed air. Shapiro (1973) and King (1970) feel that low CO_2 concentrations and high pH favor blue-greens and that the increase in the G/BG with aeration is due to increased CO_2. Our previous work (Morton et al. 1972) on CO_2 and eutrophication showed that both greens and blue-greens can efficiently utilize CO_2 at very low concentrations and high pH, but we worked with individual algae species and not mixtures. Bella (1970) feels that aeration and mixing favor the denser species. Guseva (1952) and Patrick et al. (1969) have studied the effects of manganese and concluded that high manganese concentrations inhibit the blue-greens more than the greens and diatoms. Gerloff and Skoog (1957), using the blue-green alga *Microcystis*, found that iron antagonizes or reduces the manganese toxicity.

Procedure

We have studied in the laboratory the effects of iron and manganese on the G/BG in mixtures of algae grown in batch cultures. Algae used were the green algae *Chlorella pyrenoidosa* (Wis 2005), *Dictyosphaerium pullchellum* and *Selenastrum capricornutum;* and the problem-causing blue-green algae *Anabaena circinalis* (Wis 1038), *Gloeotrichia echinulata* (Wis 1052) and *Microcystis aeruginosa* (Wis 1036). The growth medium was Hughes' (1958), modified to contain 15 mg/l N as $NaNO_3$, 0.07-7.0 mg/l P as K_2HPO_4, 10 mg/l Ca as $CaCl_2$, 7 mg/l Mg as $MgSO_4$. EDTA was not present except where noted. The medium was prepared using double glass distilled water. The light intensity was 150 ft-candles and the temperature was 23-25°C. The growth of each type of algae was followed by cell counts, while the total algal growth was also monitored by spectrophotometric measurements at 600 mμ. Manganese was added as $MnCl_2 \cdot 4H_2O$ in the concentration range of 0-1 mg/l. Iron was added as $FeCl_3 \cdot 6H_2O$ in the concentration range of 0.01-2 mg/l. Data were taken at various growth times with total algal growth from 8-150 mg/l. The initial pH range of the various solutions was between 7.2 and 7.8, which is satisfactory for both greens and blue-greens. The controls showed iron was not toxic to any of the individual algal species but that manganese did exhibit increasing toxicity with concentration to the blue-greens but not to the greens.

Results and Discussion

A few typical results are shown in Tables I and II for *Anabaena-Chlorella* and *Gloeotrichia-Chlorella* mixtures. In general, as the iron concentration increased the growth of the blue-greens was stimulated more than the greens. At about 0.1-1.0 mg/l of total iron the blue-greens started to dominate over the greens. At manganese concentrations of over 0.4 mg/l, we usually did not see a complete blue-green dominance at high iron as we did at lower manganese levels, but nevertheless there was usually a general decrease in the G/BG with increasing iron. We attribute this to the blue-green toxicity of manganese at these high levels. We found no universal relationship between the G/BG and the iron to manganese ratio, since the stimulation of blue-greens by iron occurred even with no manganese present. The G/BG's showed similar trends over a total algal biomass range of 8-150 mg/l in any given experiment, though they did vary somewhat in absolute magnitude.

The green algae *Selenastrum*, the selected species for standardized tests evaluating the nutrient potential of natural waters (EPA, 1971) and *Dictyosphaerium*, a filter clogging alga which causes problems in the Great Lakes, were substituted for *Chlorella* in experiments using *Anabaena* and *Microcystis*, and results similar to those in Tables I and II were obtained.

We do not know what is the mechanism of the stimulation of the blue-greens by iron; however, we can rule out a few possibilities. We obtained similar results over a phosphorus concentration range of 0.07-7.0 mg/l. Therefore, it seems unlikely that the iron is tying up the phosphorus, thereby permitting the blue-greens to dominate due to more favorable phosphorus uptake kinetics. We also obtained similar results with no EDTA as we did for EDTA concentrations of 0.01, 0.10, and 1.0 mg/l. This minimizes the possibility that iron may be coagulating some impurity that is toxic to the blue-greens but not to the greens, since EDTA is often used to complex metals that are toxic to blue-green algae.

Table 1. Growth of *Chlorella-Anabaena* Mixtures as Function of Iron, Manganese, and Phosphorus

Iron, mg/l	Total algae mg/l	G/BG*	Total algae mg/l	G/BG*
		P=7.0 mg/l		
	Mn=0.00 mg/l		Mn=0.10 mg/l	
0.10	10	>100	13	>100
0.30	9	>100	13	>100
1.0	12	3.1	19	0.51
2.0	15	0.32	36	0.13
		P=1.4 mg/l		
	Mn=0.30 mg/l		Mn=0.60 mg/l	
0.10	27	>100	21	>100
0.30	24	1.9	22	3.2
0.60	24	3.9	25	0.78
2.0	24	1.9	27	0.78
		P=0.21 mg/l		
	Mn=0.30 mg/l		Mn=0.40 mg/l	
0.05	9	35	18	16
0.20	12	0.26	12	0.86
1.0	12	0.32	15	0.44
		P=0.07 mg/l		
	Mn=0.00 mg/l		Mn=0.40 mg/l	
0.05	11	>100	17	14
0.20	11	5.0	25	0.91
1.0	12	0.33	23	0.24

* Green to blue-green algae ratio as determined by cell counts.

Microcystis was used as a representative of objectionable blue-green algae that are not capable of fixing nitrogen; the results were the same as with the blue-green algae *Anabaena* and *Gloeotrichia* that are nitrogen fixers. Therefore, the effects of iron are probably not related to nitrogen metabolism.

In conclusion, increases in the total iron, even when already present in excess, favor some common species of blue-greens over some greens. Therefore, consideration should be given to the total dissolved and colloidal iron in effluents. One example of this is in some wastewater phosphorus removal processes that use excess $FeCl_3$ to precipitate the phosphorus. We also feel

Table II. Growth of *Chiorella-Gloeotrichia* Mixtures as Function of Iron, Manganese, and Phosphorus

Iron mg/l	Total algae mg/l	G/BG*	Total algae mg/l	G/BG*
		P=1.4 mg/l		
	Mn=0.00 mg/l		Mn=0.10 mg/l	
0.01	60	>100	-	-
0.05	-	-	60	21
0.10	66	4.8	72	13
0.30	60	0.07	57	2.2
1.0	72	0.01	96	0.05
	Mn=0.30 mg/l		Mn=0.60 mg/l	
0.10	90	24	42	5.0
0.30	72	6.5	66	4.4
0.60	54	0.38	42	3.2
		P=0.07 mg/l		
	Mn=0.00 mg/l		Mn=0.10 mg/l	
0.05	9	>100	11	>100
0.20	12	17	11	4.9
1.0	13	2.3	18	0.61

* Green to blue-green ratio as determined by cell counts.

there are undoubtedly many factors that can affect the G/BG in a lake and that this report should be taken only to emphasize iron as one of them rather than to de-emphasize the others.

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Appendix B. Chemical Data

Figure B-1 Nitrogen Values in a Data Envelope for the Isolated Cove Lake Station, 1975-1979
Figure B-2 Nitrogen Values in a Data Envelope for the Main Body Lake Station, 1975-1979
Figure B-3 Nitrogen Values in a Data Envelope for the Boulder Brook Station, 1975-1979
Figure B-4 Nitrogen Values in a Data Envelope for the Jennings Pond Brook Station, 1975-1979
Figure B-5 Nitrogen Values in a Data Envelope for the Bogle Brook Station, 1975-1979
Figure B-6 Phosphorus Values for the Isolated Cove Lake Station, 1975-1979
Figure B-7 Phosphorus Values for the Main Body Lake Station, 1975-1979
Figure B-8 Phosphorus Values for the Boulder Brook Station, 1975-1979
Figure B-9 Phosphorus Values for the Jennings Pond Brook Station, 1975-1979
Figure B-10 Phosphorus Values for the Bogle Brook Station, 1975-1979
Figure B-11 Iron Values for the Isolated Cove Lake Station, 1975-1979
Figure B-12 Iron Values for the Main Body Lake Station, 1975-1979
Figure B-13 Iron Values for the Boulder Brook Station, 1975-1979
Figure B-14 Iron Values for the Jennings Pond Brook Station, 1975-1979
Figure B-15 Iron Values for the Bogle Brook Station, 1975-1979

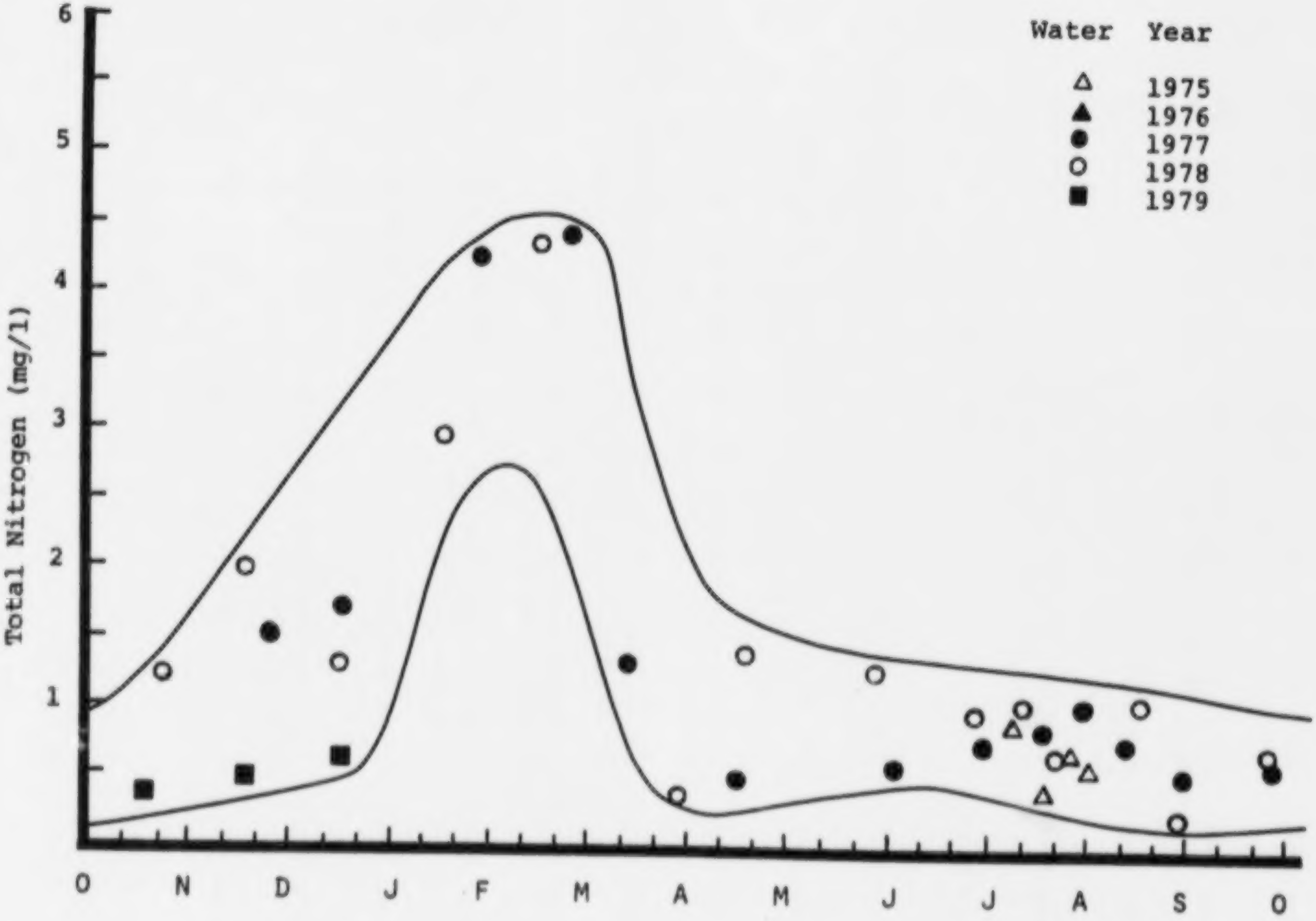


Figure B-1. Nitrogen Values in a Data Envelope for the Isolated Cove Lake Station. 1975-1979

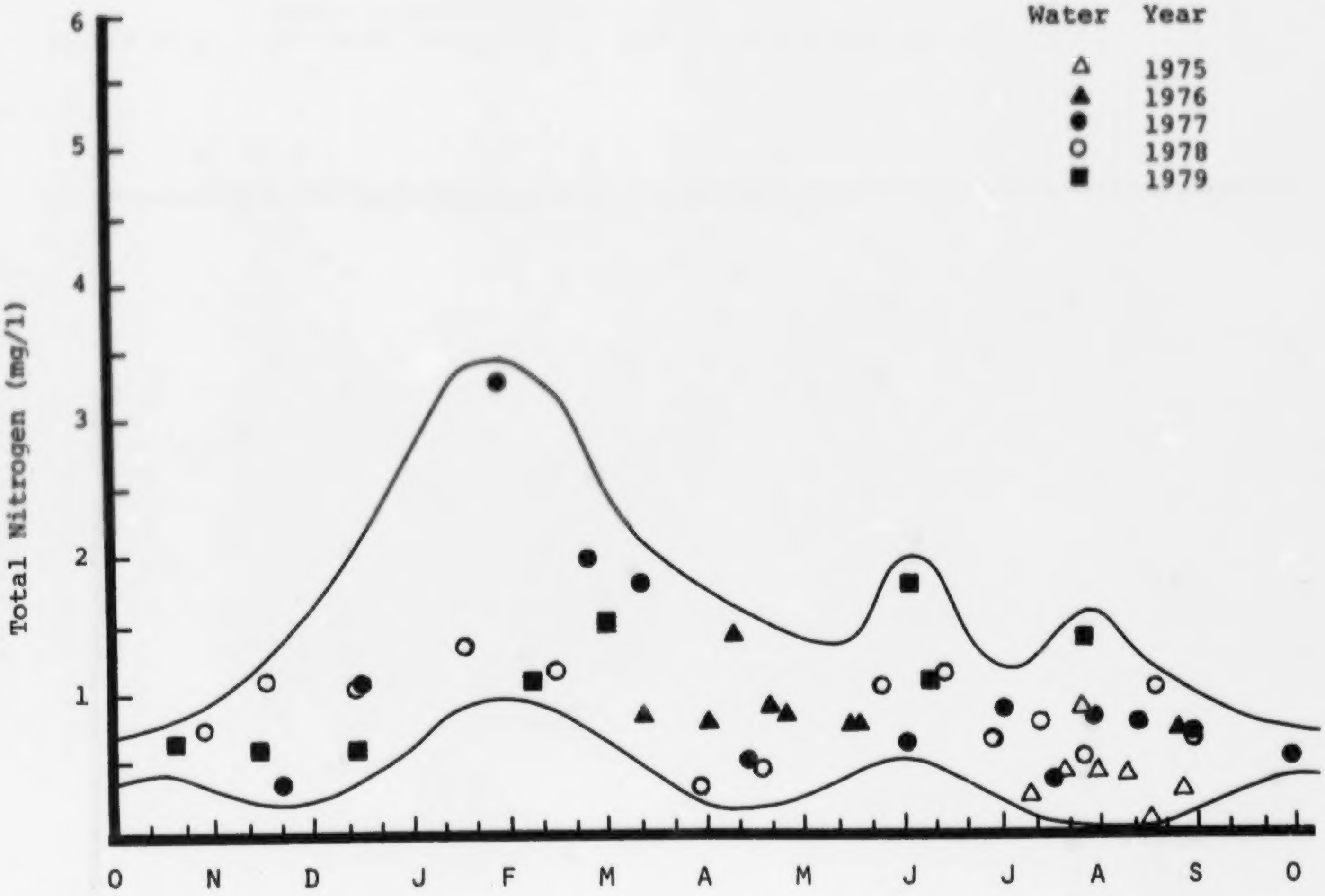


Figure B-2. Nitrogen Values in a Data Envelope for the Main Body Lake Station. 1975-1979

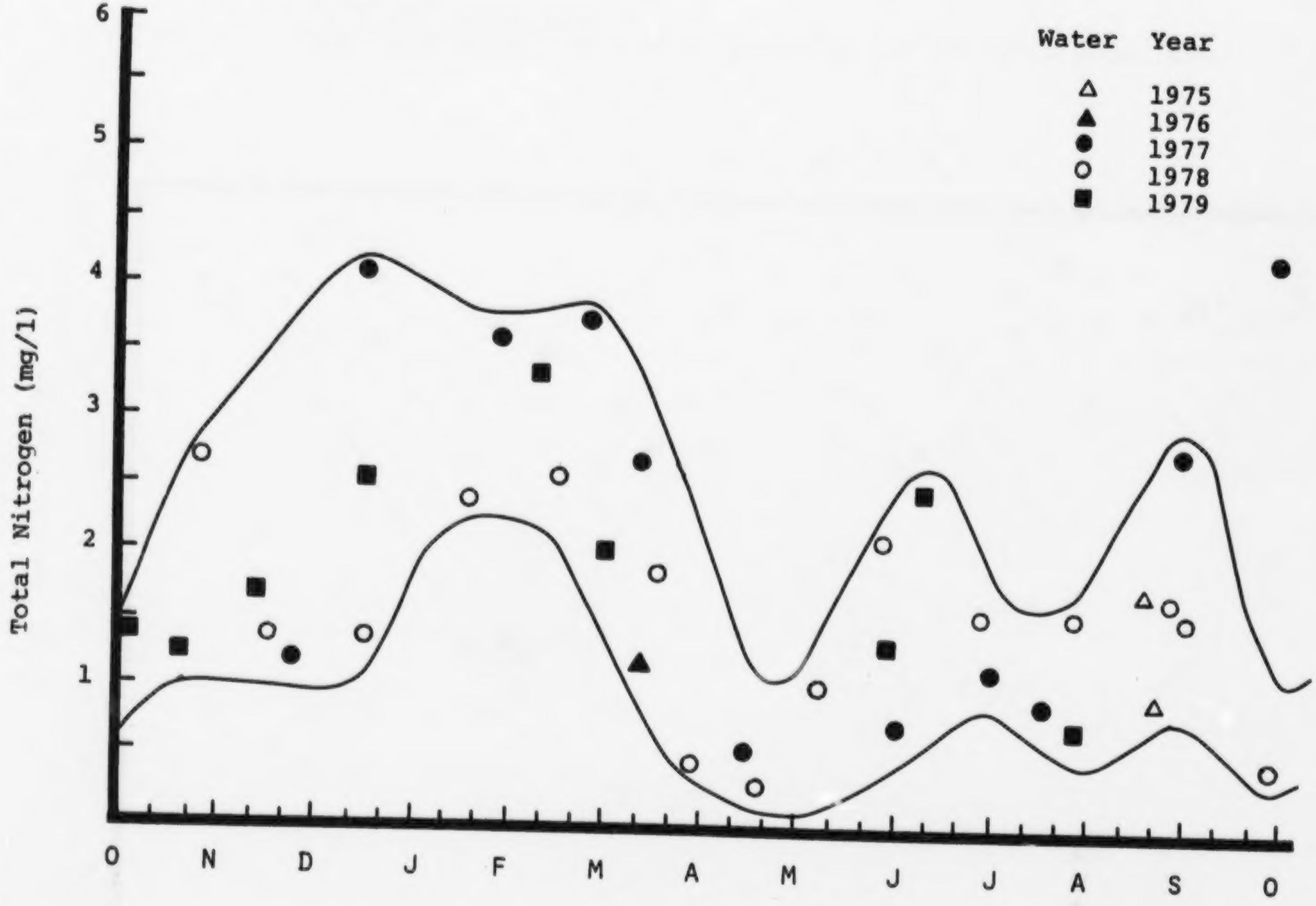


Figure B-3. Nitrogen Values in a Data Envelope for the Boulder Brook Station. (1975-1979)

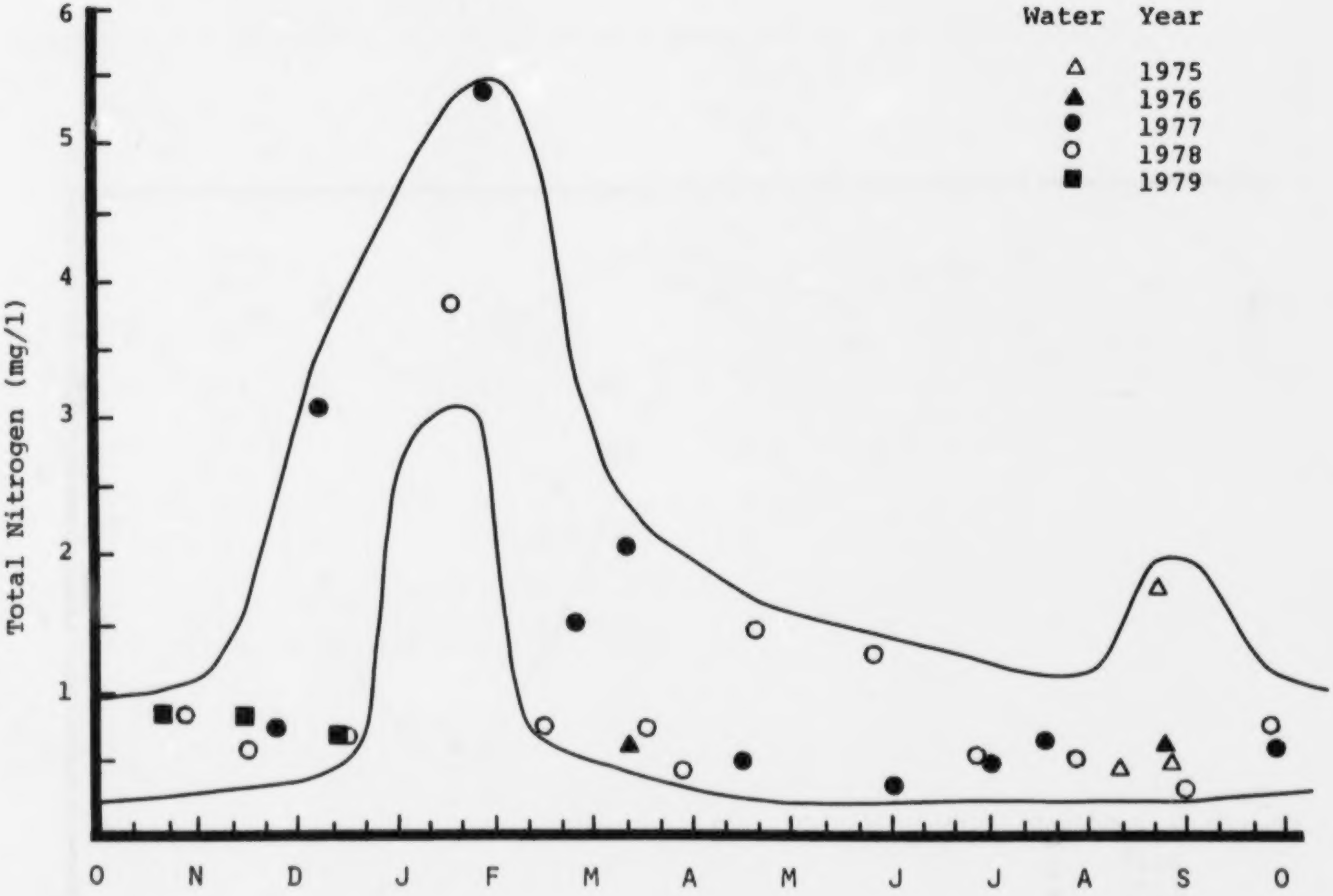


Figure B-4. Nitrogen Values in a Data Envelope for the Jennings Pond Brook Station. 1975-1979

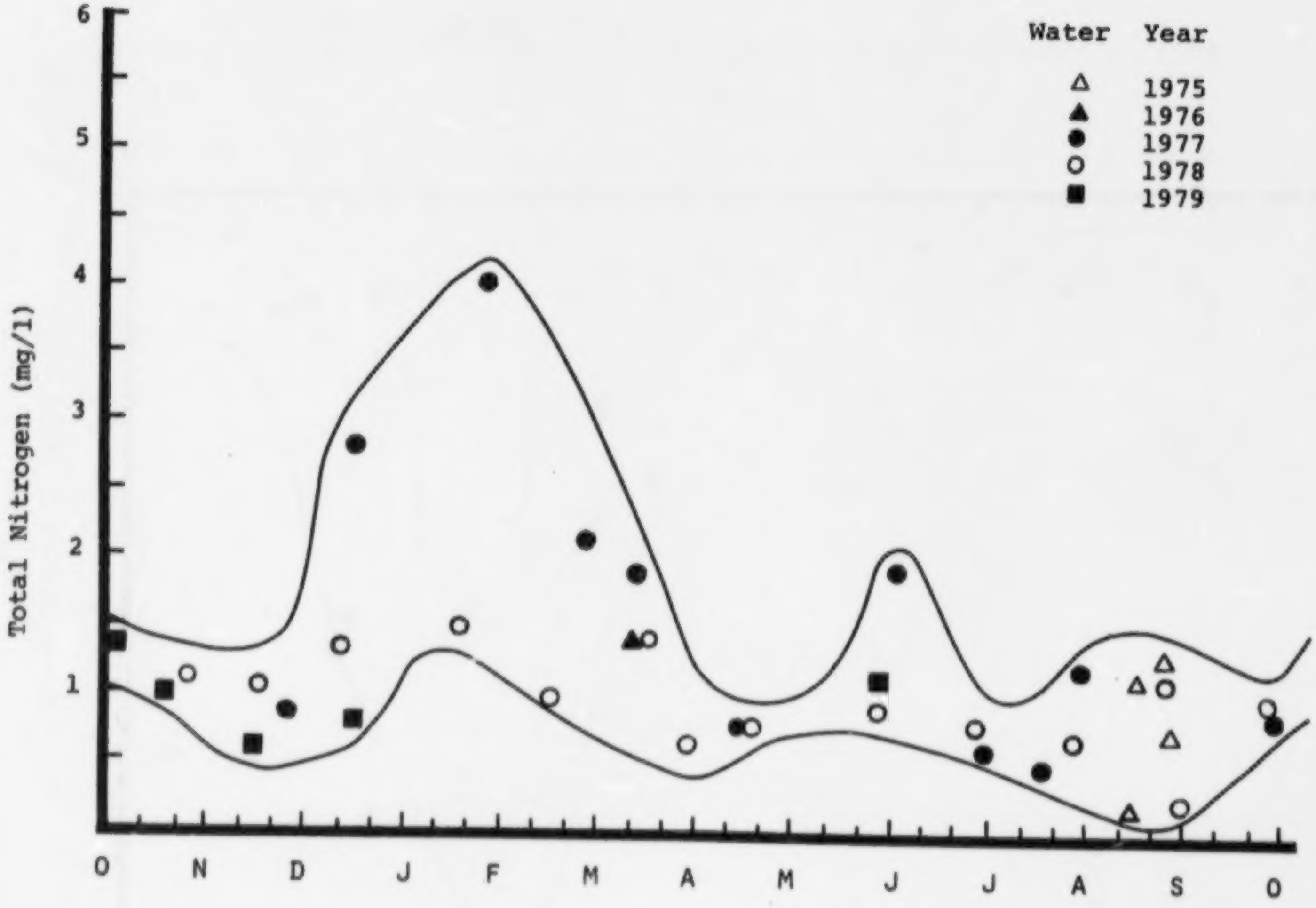


Figure B-5. Nitrogen Values in a Data Envelope for the Bogle Brook Station 1975-1979

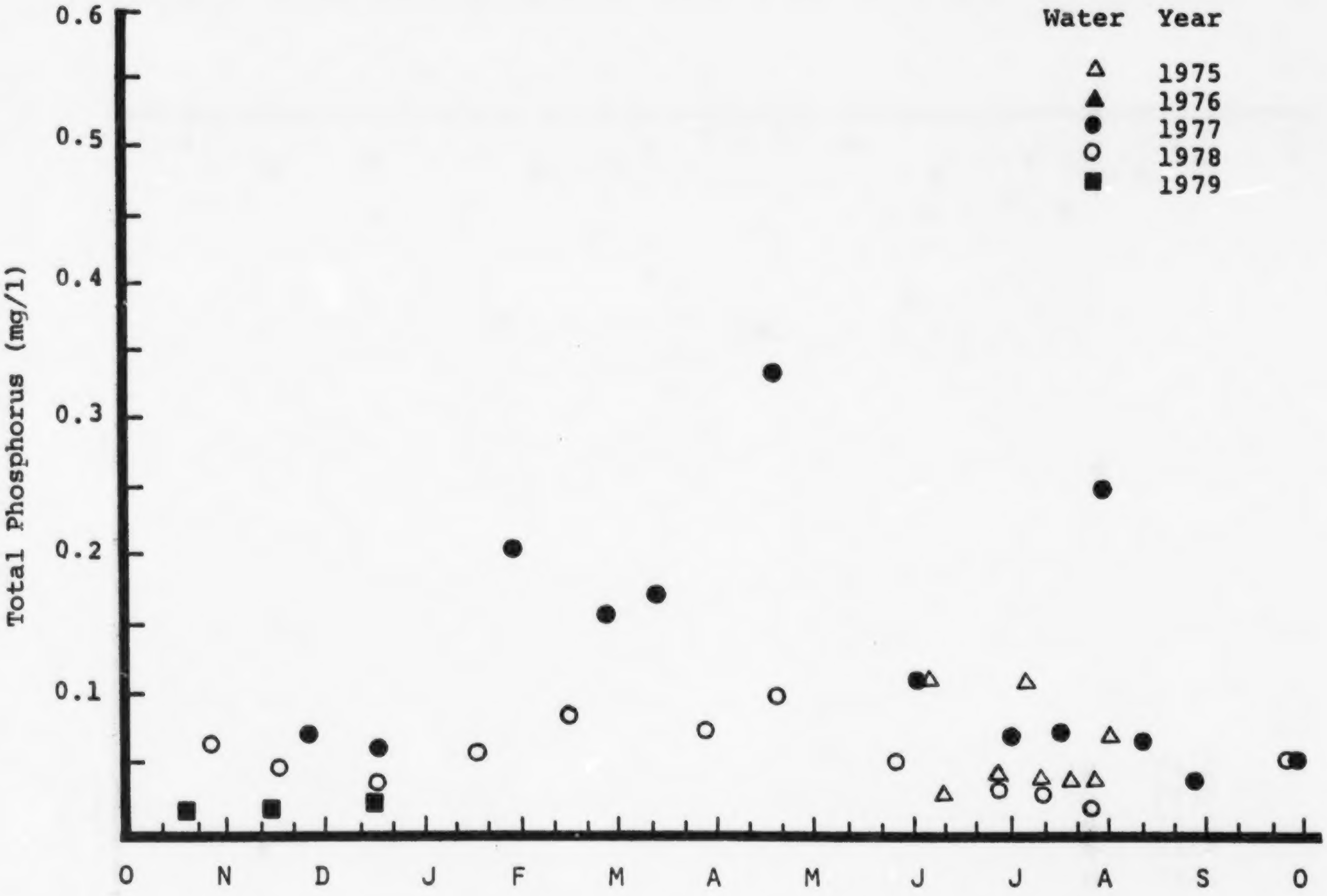


Figure B-6. Phosphorus Values for the Isolated Cove Lake Station. 1975-1979

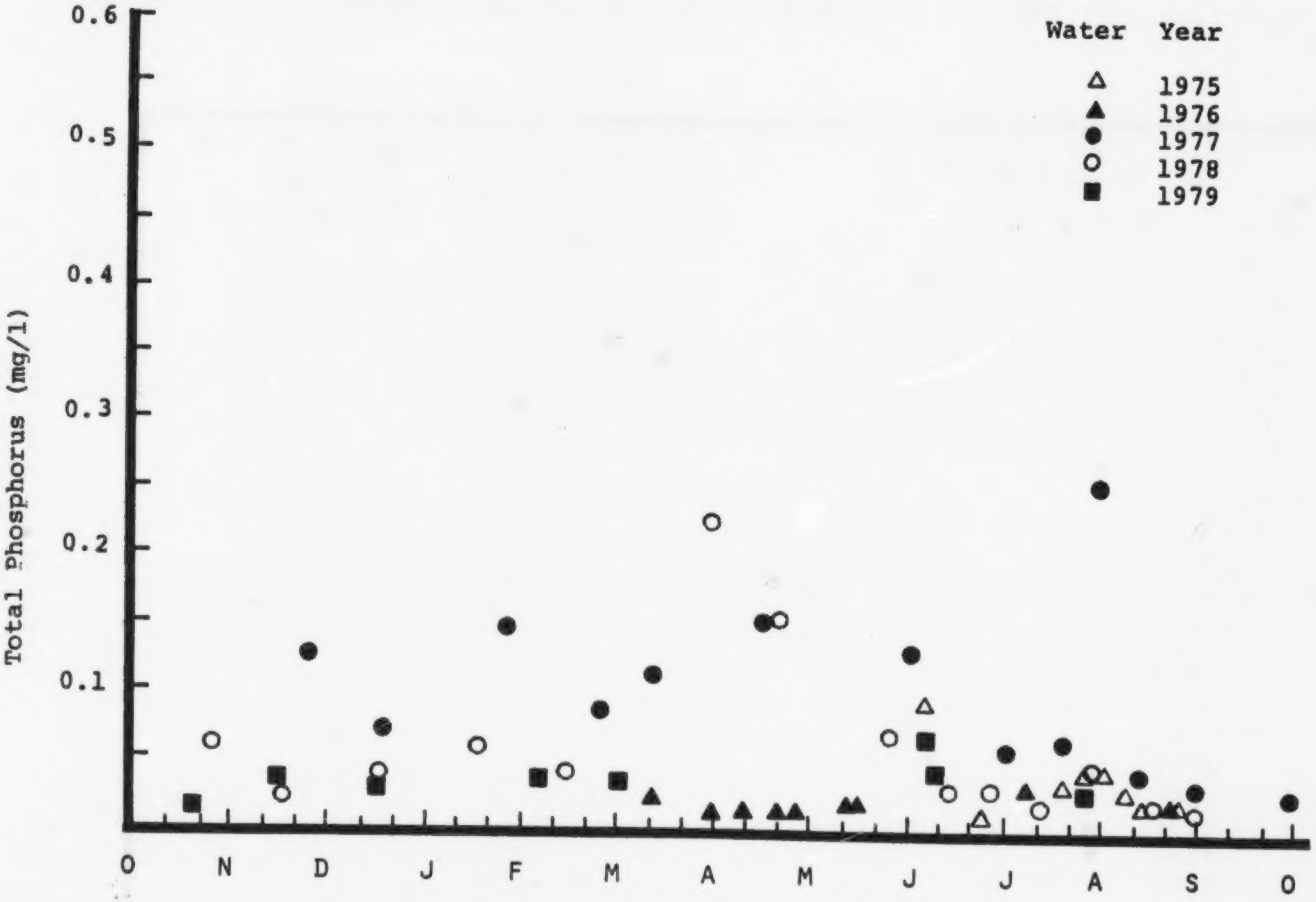


Figure B-7. Phosphorus Values for the Main Body Lake Station. 1975-1979

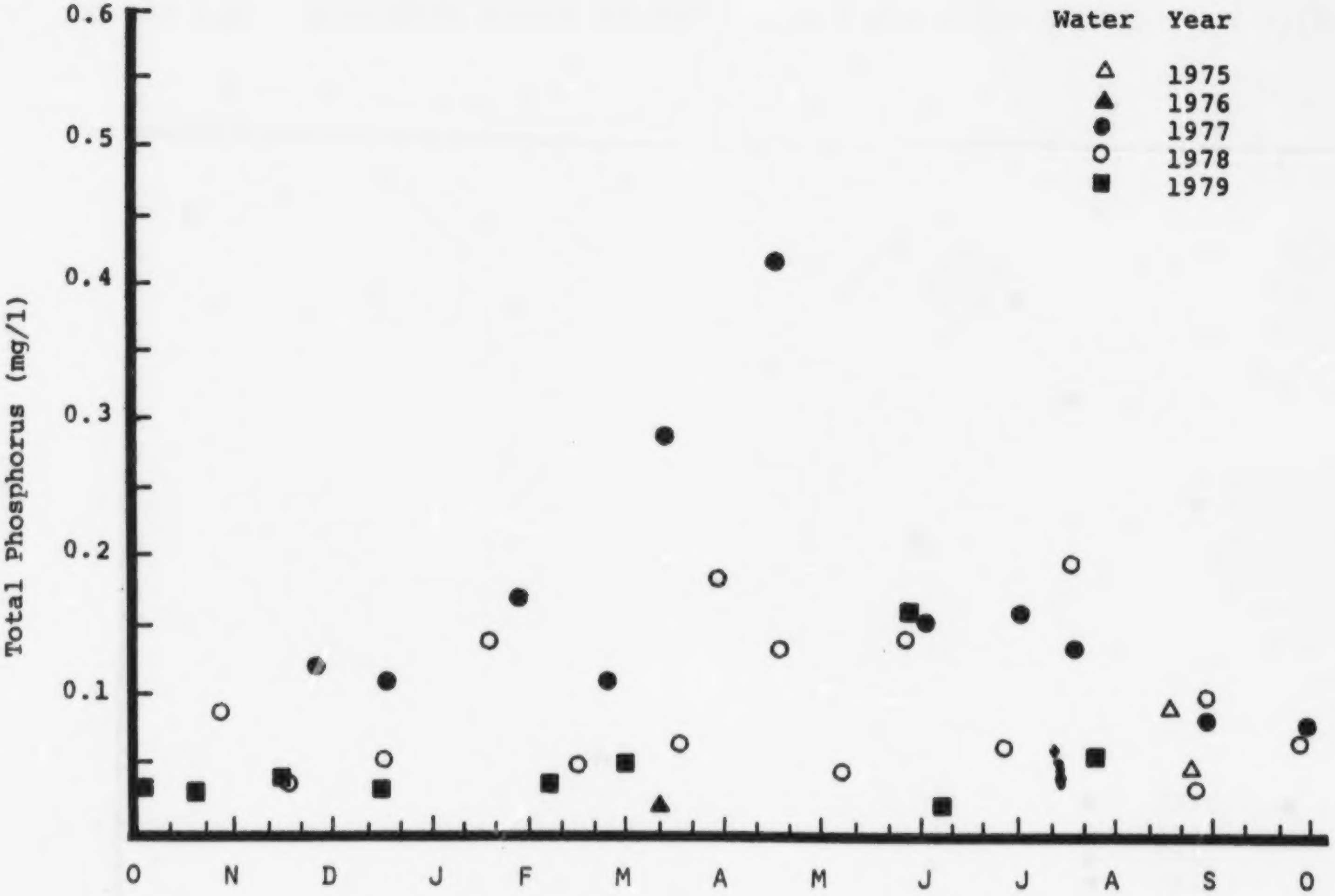


Figure B-8. Phosphorus Values for the Boulder Brook Station. 1975-1979

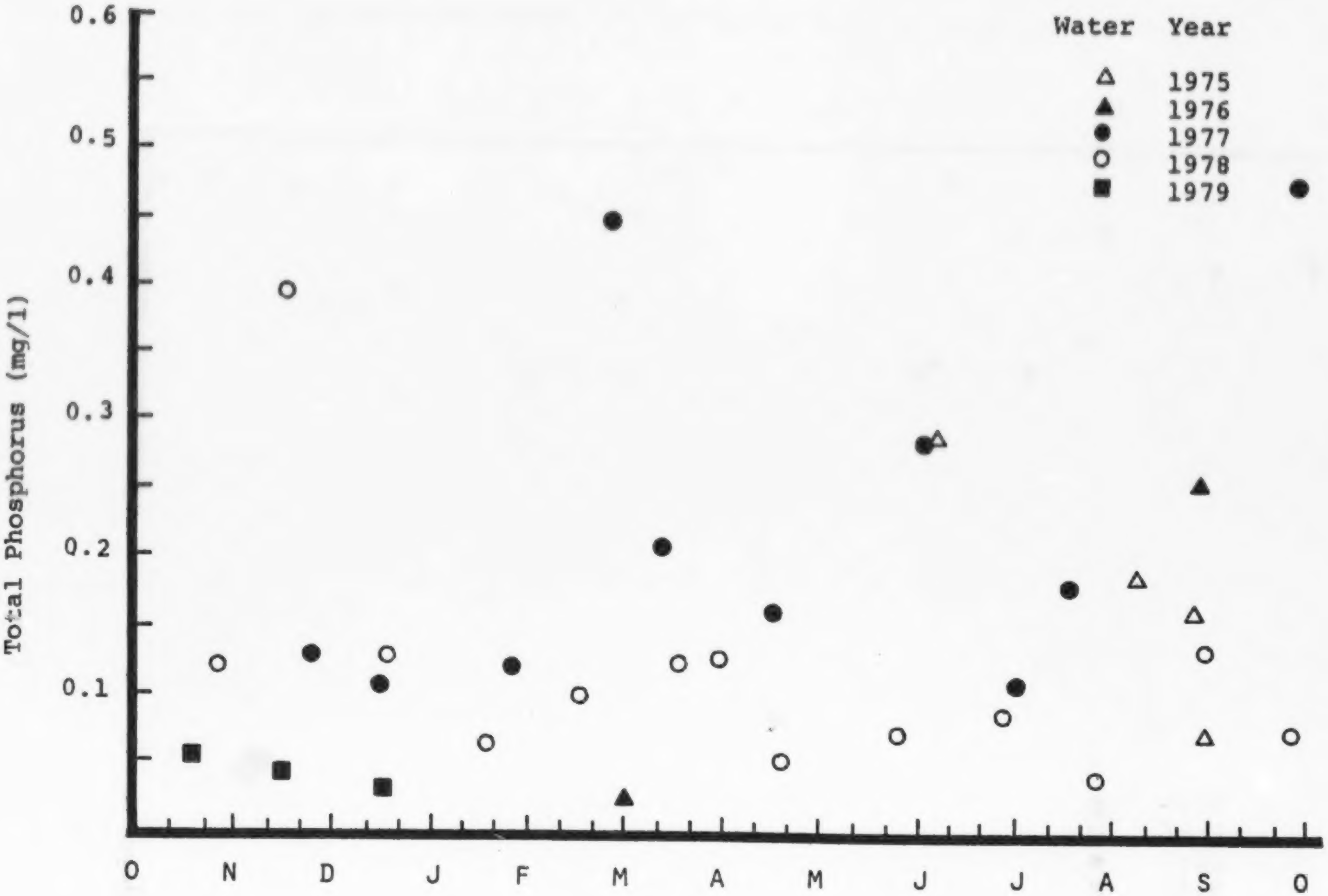


Figure B-9. Phosphorus Values for the Jennings Pond Brook Station. 1975-1979

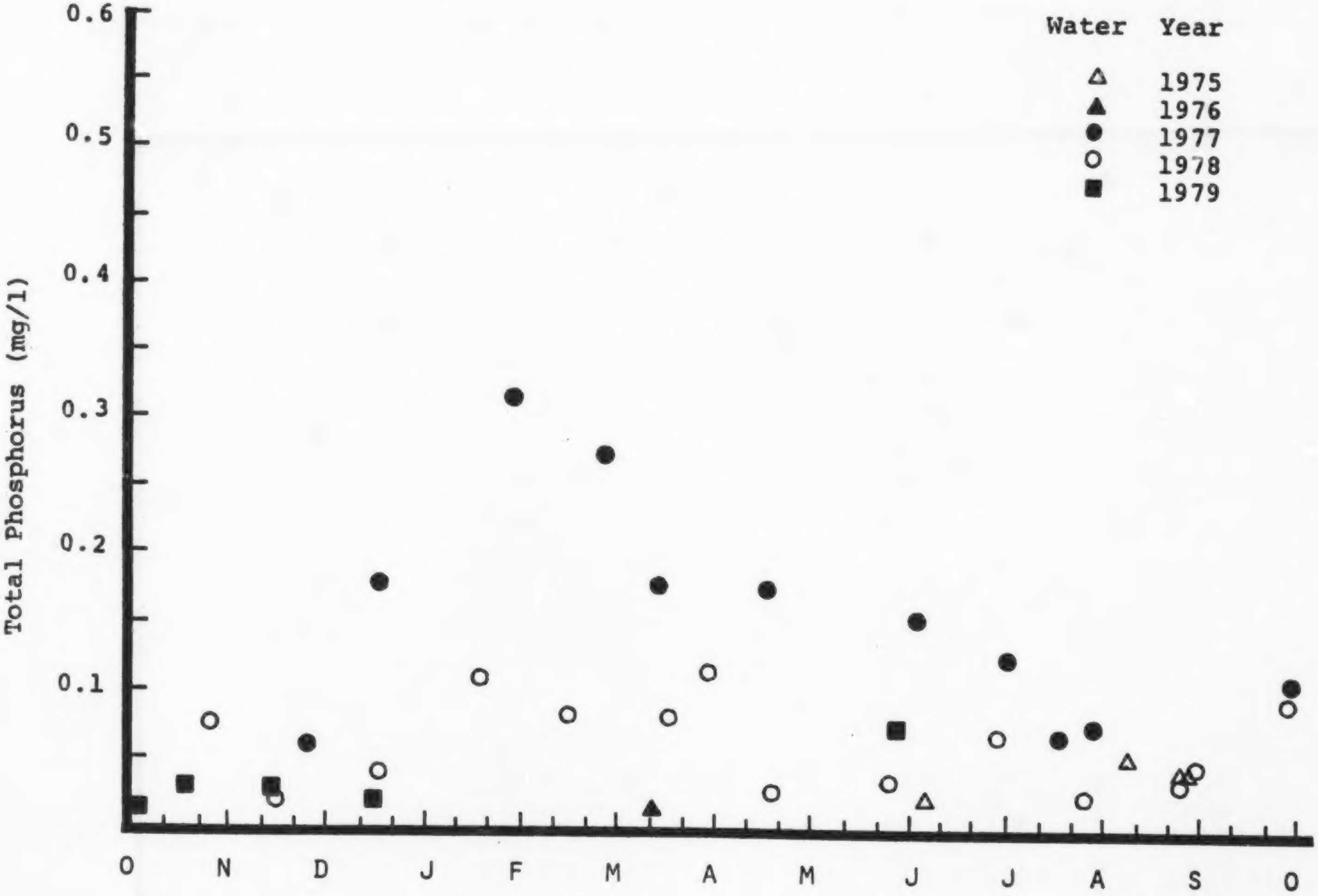


Figure B-10. Phosphorus Values for the Bogle Brook Station. 1975-1979

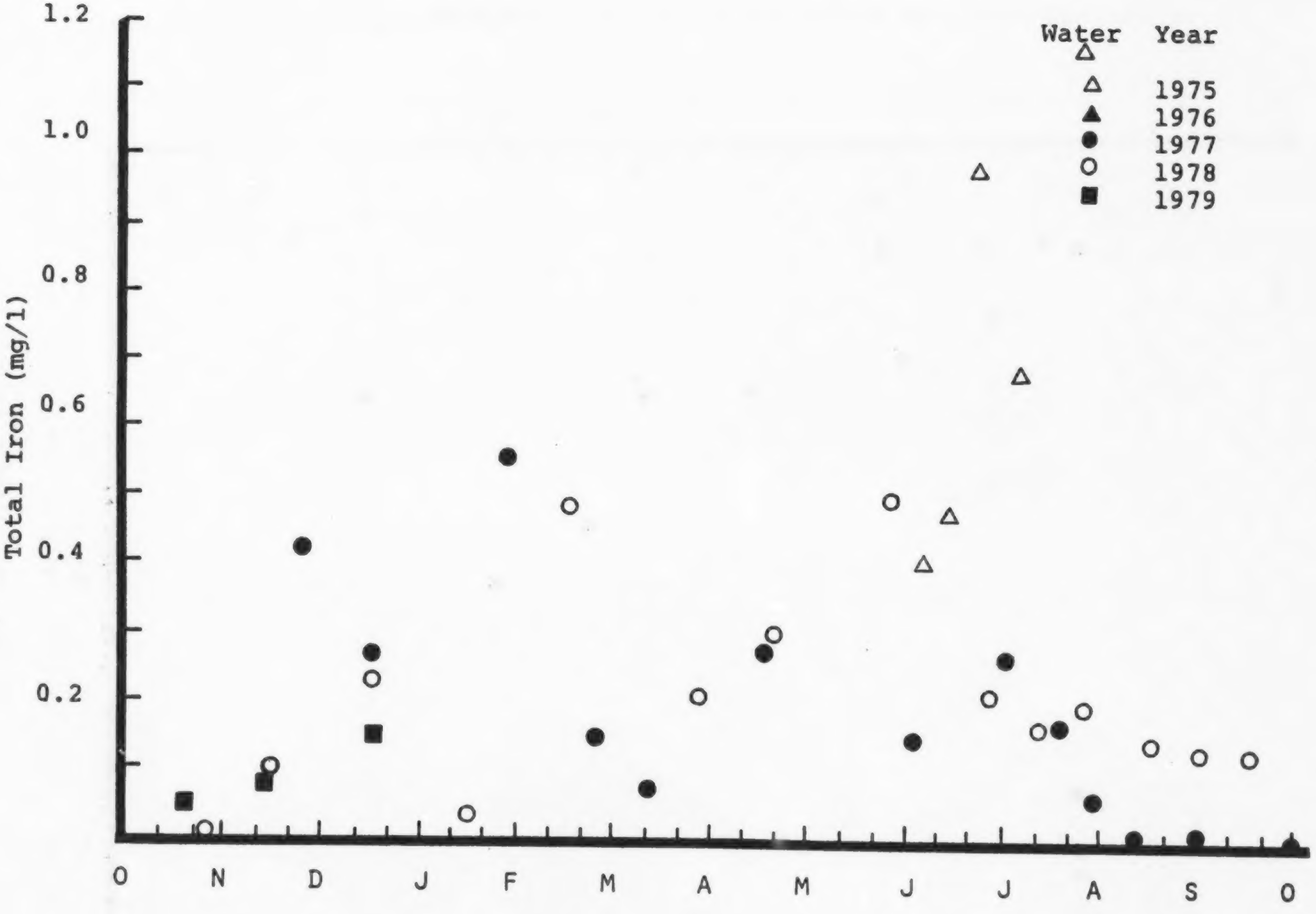


Figure B-11. Iron Values for the Isolated Cove Lake Station. 1975-1979

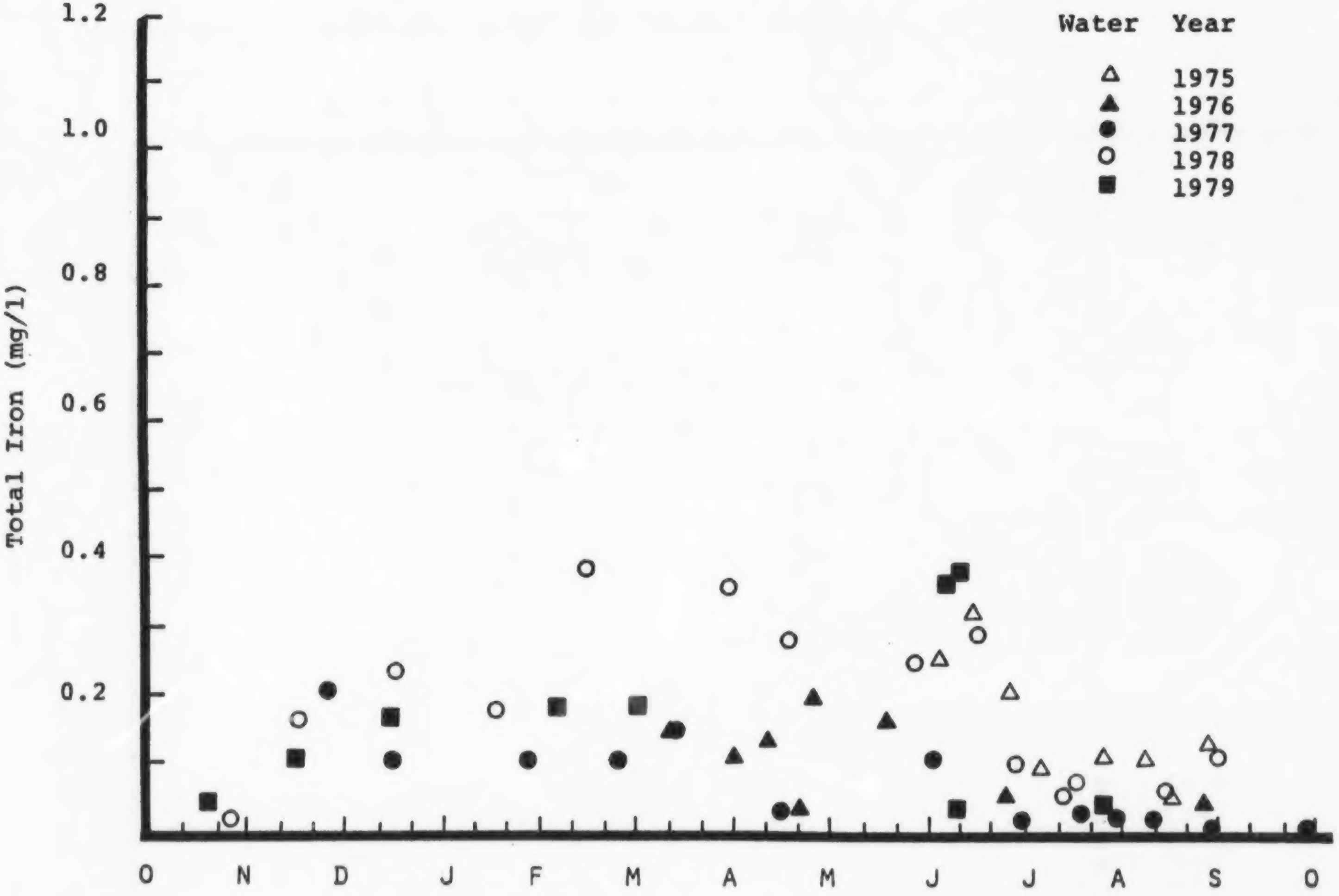


Figure B-12. Iron Values for the Main Body Lake Station. 1975-1979

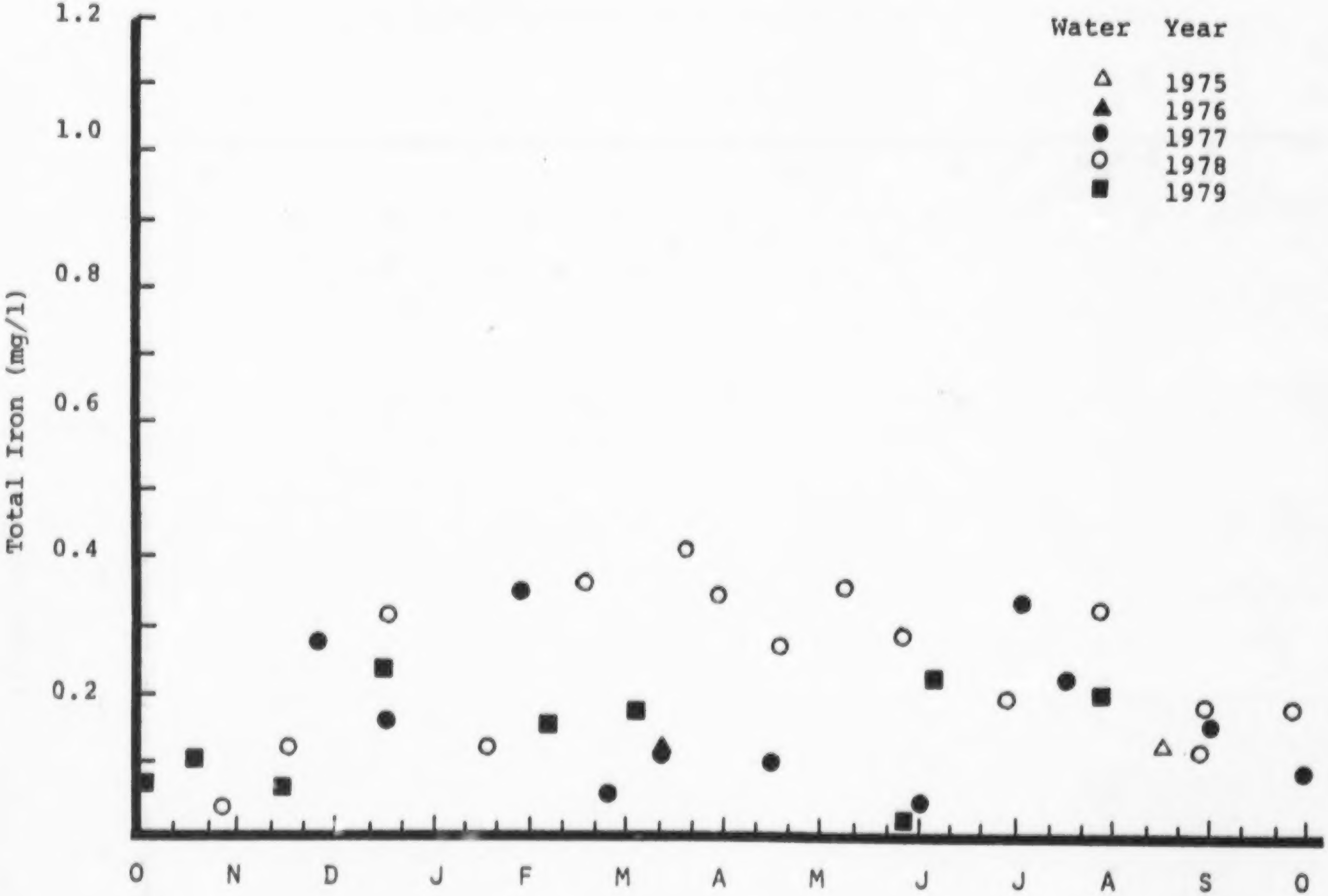


Figure B-13. Iron Values for the Boulder Brook Station. 1975-1979

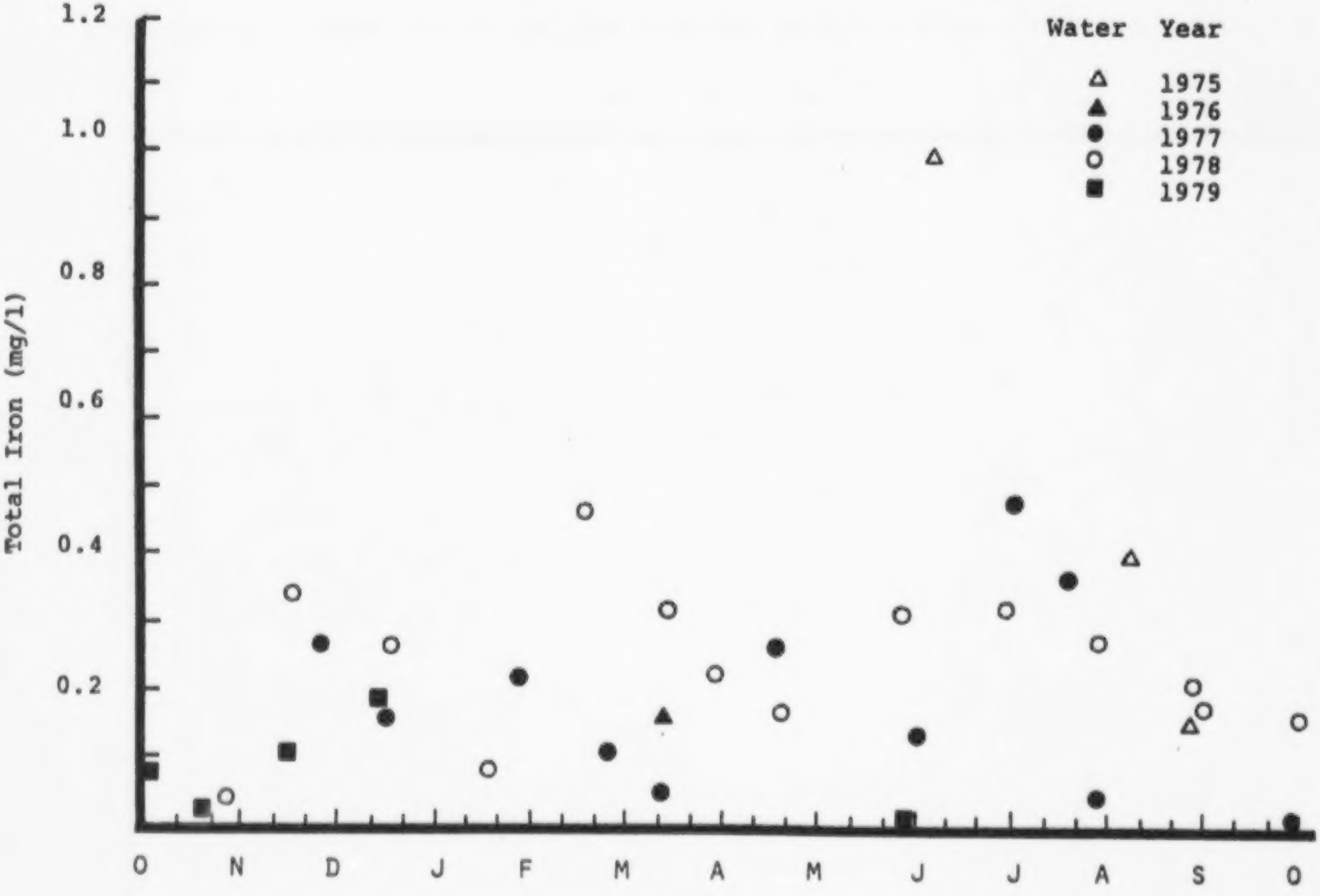


Figure B-15. Iron Values for the Bogle Brook Station. 1975-1979

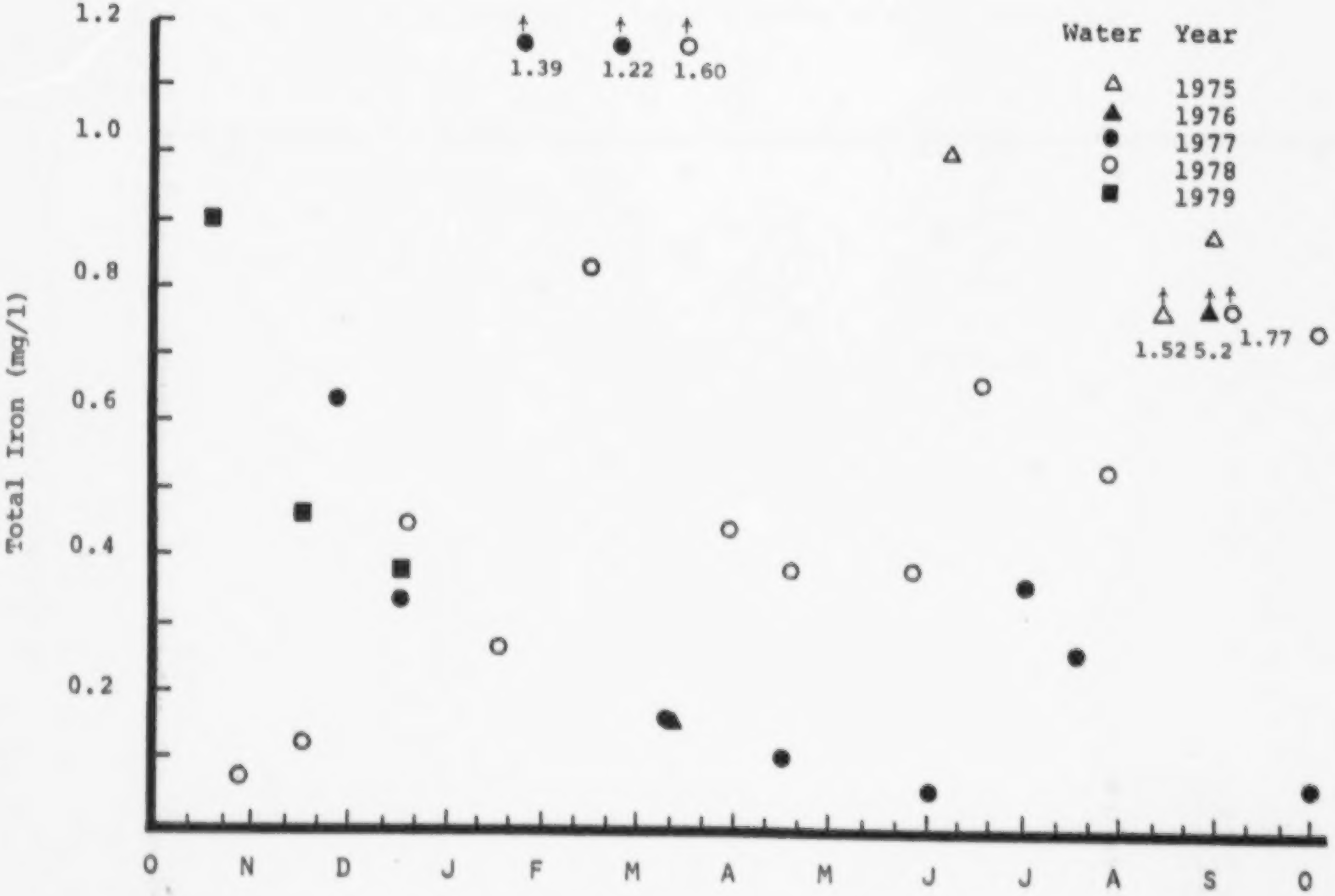


Figure B-14. Iron Values for the Jennings Pond Brook Station. 1975-1979

APPENDIX C. Methodology

All of the methods used for the data collection and sample processsing are state-of-the-art. Table C-1 lists the analysis procedures.

The phytoplankton samples were all surface samples. Surface samples were used throughout this program because the problem algae that caused reduced visibility were always in the upper meter or so of water. Samples were almost always taken between 7:30 AM and 9:00 AM. A half liter jar of water was taken at a depth of 15 cm (6 inches) as recommmended by the EPA (1975). The jar was filled so that surface film would not be drawn into the bottle. The one liter jars were only half filled to let the samples have sufficient air contact. Samples were placed in an ice filled cooler if processing was to begin after more than one hour's time. All samples since 1976 were counted live, without concentration, and most samples were under analysis within an hour. In 1974 and 1975, algal samples taken during the week were counted live but those taken over the weekend were preserved in a 5% formalin solution and kept refrigerated for analysis on Mondays. Also in 1974 and 1975, a centrifuge was used for sample concentration; whereas in later years, sample concentration was not used. From mid-1974 phytoplankton analyses were done in ASU/ml. In 1976, and thereafter, organism counts (not cell counts) were added to the ASU/ml tabulations. These latter counts have not yet been evaluated but remain available for anyone interested in population dynamics.

Visibility sampling was done in at least 2 directions to help cancel the effect of sun angle. Readings were taken while standing on the swimming dock in about 4 m (13 feet) of water. The deepest portion of the lake was not sampled because (1) extra personnel time would have been required for the boat work, (2) two persons would have been required instead of one and (3) readings in the center of the lake might not fully reflect visibility conditions in the swimming area.

The water quality sampling was always done by taking composite samples. Acid-alcohol washed one liter or one gallon plastic bottles were used for all chemical samples. The one liter samples were taken in 1975, and thereafter, one gallon samples were taken. Each lake sample was made by taking one-third of a container of water from a separate location in the general sampling area. Stream samples were taken at one-third container every five minutes and 3 samples were integrated into each final sample. This time-space composite technique was used to eliminate the patchiness in chemical properties of flow regimes. Beginning in 1976, all samples were placed on ice as soon as taken and were delivered to the chemical laboratory before the end of the day. Processing began within 24 hours of delivery. Only storm samples taken on weekends had preservative added. Storm samples, and all chemical samples taken in 1975 were preserved and processed within a few weeks. Preservative techniques using H_2SO_4 and HNO_3 are described by the U.S. EPA (1974).

General water chemistry samples were processed by LaPuck Laboratories Inc. for the first two years of the state and federal funding (starting Oct. 1976) and by Arnold Greene Laboratories, Inc. in all other years except 1975 when the state lab at Lawrence processed the nutrient samples and Boston College processed the cation and metal samples. Arnold Greene Laboratories, Inc. processed all chemical analyses involving plant fluids and sediments. Both laboratories are state certified and use EPA quality control techniques defined in Handbook for Analytical Quality Control in Water and Wastewater Laboratories, U.S. EPA, Analytical Quality Control Laboratory, National Environmental Research Center, Cincinnati, Ohio, June 1974. In addition, the Arnold Green Laboratory, Inc. has been a participant in the EPA Voluntary Laboratory Proficiency Study for six years. In the last year of this program, blind EPA standards were given to Arnold Greene Laboratory, Inc. and these results were satisfactory.

In-situ physio-chemical testing included pH, Eh, DO, temperature, conductivity, turbidity and color. Equipment used is defined in Table C-1. The storm sampling procedure is defined in Section 5.8 of this report.

The periphyton sampling methodology was straightforward. A known area was sampled. The periphyton was washed and hand picked free of sediment and leaves. Then the materials were weighed and dried or processed for chemical treatment according to the methods listed in Table C-1. Some of the initial sampling was done in a quarter square meter aluminum frame with the area cleared by a diver. This proved to be difficult due to clouds of sediment raised with the initial disturbance of the bottom. Most of the work on periphyton biomass was done with a 232 square cm (36 square inches) petit ponar dredge. However, this proved less than satisfactory in those instances when the dredge didn't close or when a rock jammed the jaws of the dredge allowing material to escape. In these cases, the boat had to be moved to be sure samples were taken from undisturbed areas. Sampling late in the program was done with a 0.113 sq. m. (1.2 sq. ft.) aluminum can with the bottom removed. This allowed a diver to place the can over the sample area and then the area could be cleared of periphyton without any significant sampling error. Periphyton that became dislodged in the first sampling attempt would stay in the trash can and resettle. Thus the periphyton could be totally collected by repeated collection until it was essentially all recovered. All samples were reduced to gm/m^2 for comparison of the sampling methods. For sampling through the ice, grab samples were taken by a four pronged claw. These grab samples were used for chemical analysis but not for biomass determinations.

The aquatic plant surveys were made with multiple stations along a number of transects. Over 130 stations covering the north end of the lake were occupied in 1977 and 1978. More stations were added in 1979 following the dredging. At each station, percentage coverage by plants was estimated by first visually evaluating plants within 20 feet of the boat and then by checking the bottom for periphton and low profile plants with a long handled claw.This ensured inclusion of low profile aquatic macrophytes and periphyton. Two professionals independently evaluated each station and differences were resolved on the spot by discussion and re-evaluation.

The method for mapping lake currents (shown in Figure 2) is direct observation. Most observations were of floating debris which moved rapidly in the well developed current system. For several areas where current velocities were low, dye releases were used to determine current directions. Surface slicks were easily observed while boating and transport of suspended matter was easily observed near these slicks.

Table C-1. Methodology

P-t	Total Phosphorus: Persulfate Digestion / Stannous Chloride
P-o	Ortho-Phosphate: Stannous Chloride
Kj-N	Kjeldahl Nitrogen (total): Digestion / Specific Ion Ammonia Probe
NH_3-N	Ammonia Nitrogen: Specific Ion Ammonia Probe
NO_3-N	Nitrate Nitrogen: Cadmium Reduction
NO_2-N	Nitrite Nitrogen: Diazotization
Fe	Total Unfiltered Iron: Atomic Absorption
Alk	Alkalinity: Acid Based Titration
Ch-a	Chlorophyl-a: SCOR/UNESCO in Hydrobotanical Methods by Richard Wood (1975)
Na	Sodium: Atomic Absorption
K	Potassium: Atomic Absorption
Mg	Magnesium: Atomic Absorption
Ca	Calcium: Atomic Absorption
Cl	Chloride: (Halogen Electrode) Portable pH Meter, Cat 7417 Leeds and Northrup Co.
Cond	Conductivity: Salinity-Conductivity- Temperature Meter Yellow Springs Instrument Co. Model 33
Temp °C	Water Temperature in degrees Calvin: From a Mercury Thermometer
pH	Hydrogen-ion Activity: (pH Electrode) Portable pH Meter Leeds and Northrup Co. Cat 7414
Eh	Oxidation-Reduction Potential: (Redox Electrode) Portable pH Meter Leeds and Northrup Cat 7414
Color	in Alpha-Platinum Cobalt Standard Units: Hach Chemical Co. DC 16544 DR
D.O.	Dissolved Oxygen: Modified Azide-Winkler Method with Drop Count Titration

Methodology (Continued)

Phytoplankton in Areal Standard Units per Millimeter (ASU/ml)

Tot.Col. Total Coliform Bacteria: Membrane Filter Method
Number of Organisms Per 100ml.

Fec.Col. Fecal Coliform Bacteria: Membrane Filter Method
In same Units as Tot.Col.

Fec.Strep. Fecal Streptococci Bacteria: Membrane Filter Method
In Organisms Per 100ml.

Vis. Visibility in Feet: Measured by an 8 inch Secchi Disc

Flow Flow is in Cubic Meters Per Second(CMS): Calibration at
Control points with Pygmy Type Current
Meter No. 625F, W. and L.E. Gurley Co.

APPENDIX D.

Water Quality Impacts from Dredging and Analysis of Organic Sediments

On Friday, 10 November, a field trip was conducted to inspect and evaluate the dredging operation at Morses Pond, Wellesley, Massachusetts. Water quality samples were taken in the open area of the lake, in one of the channels between the islands at the north end of the lake, in the actual dredging plume, and in a control area. An additional sample was taken from the spoils pipe when the pipe accidentally parted at a joint while the pipe's position was being adjusted. The sampling locations are shown in Figure D-1.

At location A, the open water sample hinted at some possible impact of dredging but the laboratory tests showed zero turbidity. At location B, the water clearly indicated some dredging impact and the actual turbidity was 30 FTU (Formazin Turbidity Units). At location B, the water sample indicated no sign of increased nutrients except for a small increase in iron content. This higher iron content was well within the range of values previously observed in Morses Pond. Thus, except for the small increase in turbidity, there was no impact observed in the channel. The other two channels were not evaluated because they were used for passage of the dredging workboat and were disturbed by this vessel.

At location C, a sample was taken directly from the plume of the dredge. This sample was allowed to stand for one hour, duplicating the procedure used in the Standard Elutriate Test. A control sample was taken at location D where there was no evidence of dredging except for a thin oil slick. In the plume itself, there was no significant increase in ortho-phosphate, nitrate or nitrite-nitrogen when compared with the control samples at A and D. Items that did increase were total phosphorus, total Kjeldahl nitrogen and ammonia-nitrogen. Of these items, ammonia is the greatest concern because it is toxic to many aquatic organisms if present in high concentrations. At all locations, ammonia nitrogen levels were well below 1.5 mg/l which is the general guideline for fresh water systems. All values are also below the 2.8 mg/l ammonia nitrogen concentration which would contain 0.02 mg/l un-ionized ammonia that could yield aquatic toxicity at 10°C (50°F).

The increase in total phosphorus was due to fine particles in suspension. About 60% of the increase in total Kjeldahl nitrogen was due to the ammonia increase discussed above. The remaining 40% would be largely due to particles in suspension.

As for the oil slick resulting from the dredging, it was expected because oil from nearby Route 9 drained into the north end of the lake over the past years and was trapped in the sediments. This oil was released by the turbulence associated with the dredging. The slick did not appear to be thick enough or extensive enough to have any significant impact.

During the site inspection, the dredging crew was adjusting the position of the pipe with the workboat. At that time, one of the pipe joints accidentally parted and the dredge was shut off. After the dredge was shut off, the entire pipeline emptied at the break which is shown as station E on Figure D-1. A sample was taken right from the pipeline as it emptied. The nutrient values from this sample were all satisfactory after the one hour settling period, with particulates contributing to the high total phosphorus and total Kjeldahl nitrogen values.

About one hour after the pipeline broke, a deep sample was taken at location F. Even with the broken pipline acting as a sediment source, the turbidity one foot from the lake bottom was only 25 FTU. It is assumed that almost all of this value was caused by the break in the pipeline. All test results are presented in Table D-1.

With the exception of this break in the pipeline, no significant leakage of the pipeline was observed. At most pipe joints, the pipe was sealed by an externally clamped rubber gasket. In some locations, thin wooden staves were used to seal the joints and these appeared to be working nicely.

While evaluating the dredging operation, noise level readings were taken at location B. Noise readings of the operating dredge were tightly grouped with the entire range of observations spanning only 3.5 dbA. The median value at a distance of about 125 meters was 74.2 dbA. Values at 3 meters from the dredging barge indicated a near-field noise value of 95 dbA.

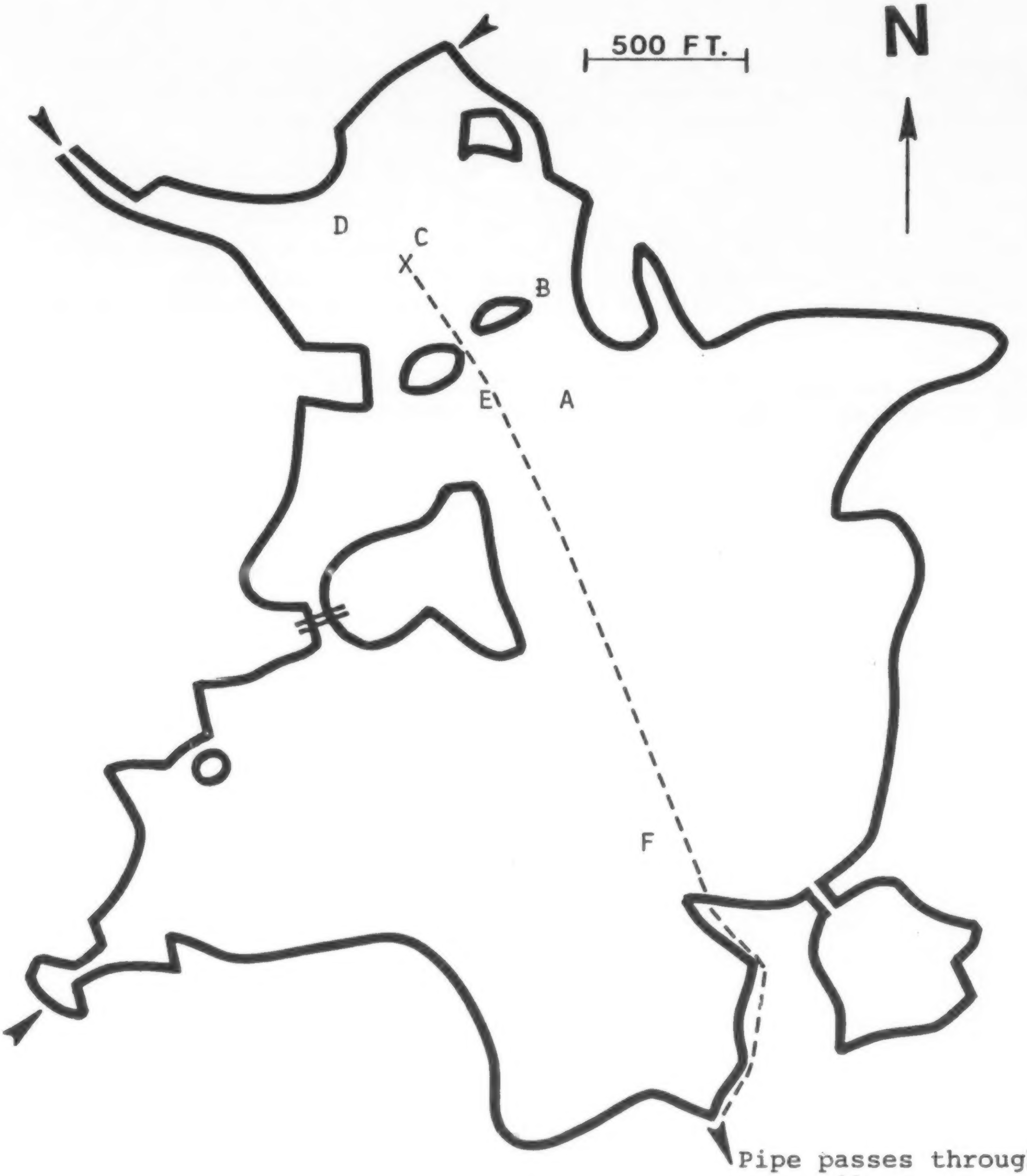
During the first stages of dredging, many visits to the spoils area were made. No odors from the spoils area were detected. This may be partially due to the cool temperatures in October and November which increase the oxygen content of the water and decrease rates of bacterial action which accompany decay processes.

In addition, during the first few weeks of dredging, infiltration within the spoils area was significant and no water was discharged through the sand filter. Sand filter function later in the operation is discussed in section 7.1 of the report.

The only problem noted during the early stages of dredging was some erosion of the inside wall of the spoils area berm. This occurred just below the pipe discharging into the spoils area. This was corrected by backfilling the eroded area and by extending the discharge pipe further past the berm.

Based on the observations and initial test data, it was concluded that the initial stages of the dredging operation were proceeding in an environmentally acceptable manner. This interim report was made to satisfy the specific state requirement that the first $20,000 worth of dredging be evaluated by the principal investigator of the lake restoration research and demonstration grant.

Chemical analyses of the organic sediments in the dredged area are presented in Table D-2 for locations shown in Figure D-2.



Pipe passes through culvert to spoils area.

Figure D-1. Sampling Locations for Evaluation of Dredging in Morses Pond.

A = Open Water Sample.
B = Channel Sample Leading to Open Water.
C = Sample in Dredge Plume.
D = Sample of water unaffected by day's dredging.
E = Sample from Broken Spoils Pipe.
X = Dredge Location.
- = Pipeline for Spoils.
F = Van Dorn Sample in Deep Area, One Foot from Bottom.

TABLE D-1. Water Quality Test Results During Dredging. Samples were taken on November 10, 1978 while the dredge was actively operating. All units are in mg/l except for turbidity which is in Formazin Turbidity Units (FTU). for station descriptions see page one of this appendix.

Station	A	B	C	D	E	F
Total Phosphorus	0.03	0.03	0.19	0.14	0.17	-
Ortho-Phosphate	0.02	0.02	0.03	0.03	0.03	-
Total Kjeldahl Nitrogen	0.55	0.50	1.45	0.65	6.8	-
Ammonia Nitrogen	0.05	0.05	0.56	0.06	0.30	-
Nitrate Nitrogen	0.09	0.05	0.09	0.05	0.08	-
Nitrite Nitrogen	<0.005	<0.005	0.007	<0.005	0.011	-
Total Alkalinity (as $CaCO_3$)	27.8	34.0	31.5	34.4	22.8	-
Total Unfiltered Iron	0.13	0.19	*	0.32	*	-
Turbidity	zero	30	125	zero	NA	25

* Sample not properly processed.

TABLE D-2. Chemical Analyses of Fresh Organic Sediments from Morses Pond. Nutrient samples were collected in February 1978. The sample for metal and organic analyses was taken in May of 1977. Sample locations are shown in Figure D-2. Samples were taken with a posthole digger.

Station #	1	2	3	
Extractable NH_3-N	0.44	0.48	0.52	mg/100gms
Extractable NO_3-N	0.04	<0.02	0.03	"
Extractable NO_2-N	0.003	0.004	0.003	"
Extractable P	0.012	0.034	0.012	"
Percent Solids	39.4%	26.8%	9.0%	
Loss on Ignition (550°C)	6.9%	5.6%	6.8%	

Emission Spectrographic Analysis (Range %)

Aluminum	0.06 - 0.6	Manganese	0.002 - 0.02
Antimony	<0.0001	Mercury	<0.0004
Arsenic	<0.0001	Nickel	0.0002 - 0.002
Cadmium	<0.0001	Silicon	0.0002 - 0.002
Calcium	0.06 - 0.6	Silver	<0.0001
Chromium	0.0002 - 0.002	Sodium	0.0002 - 0.002
Copper	0.0002 - 0.002	Thallium	<0.0001
Iron	0.2 - 2.0	Tin	<0.0001
Lead	0.006 - 0.06	Titanium	0.0002 - 0.002
Magnesium	0.06 - 0.6	Zinc	0.002 - 0.02

Mass Spectrographic Analysis for Organics

Benzene	20 mg/kg	Toluene	20 mg/kg

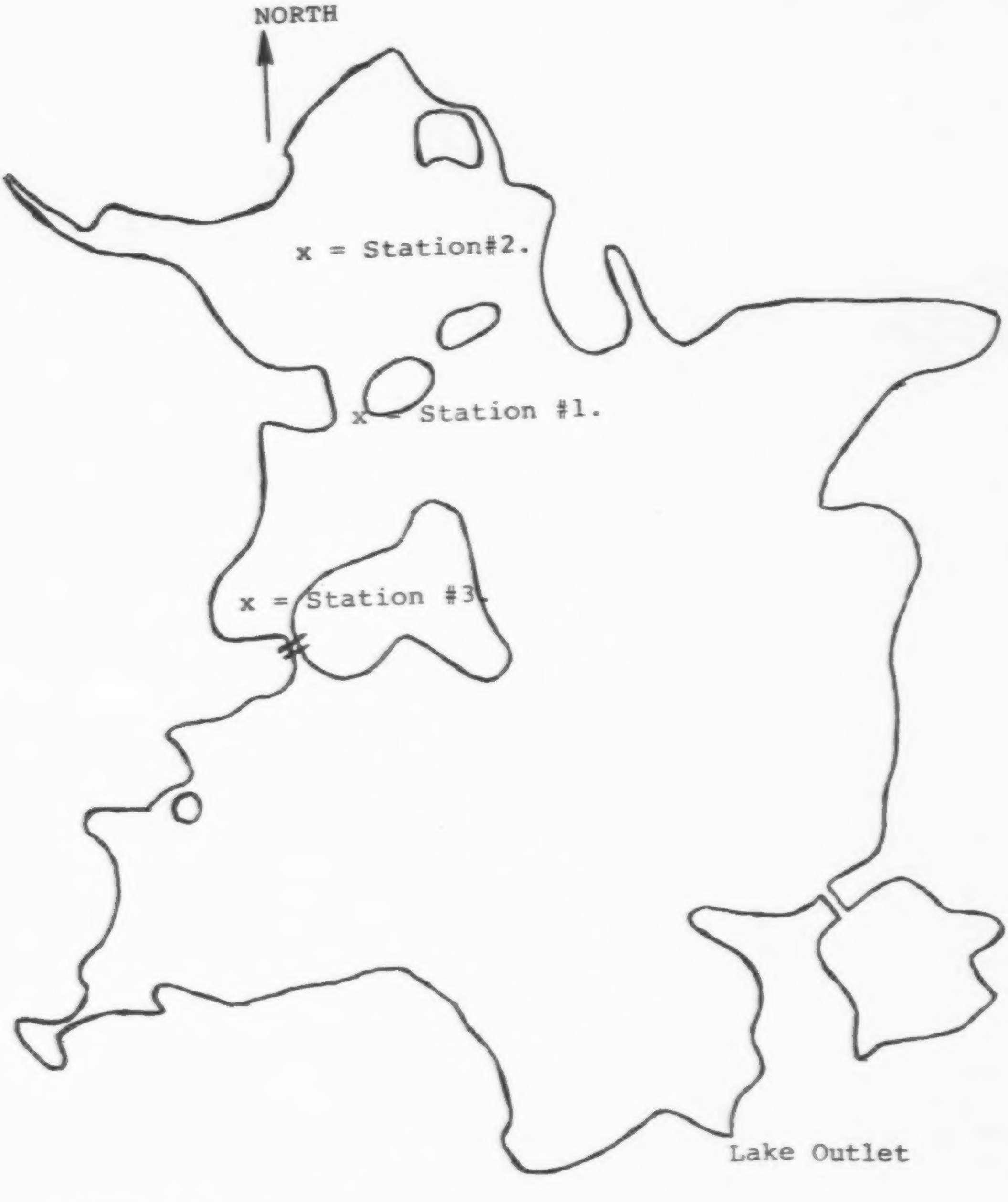

NORTH
x = Station#2.
x = Station #1.
x = Station #3.
Lake Outlet

Figure D-2. Location of Sampling Stations for Sediment Analyses. The location of the station for metals and organic analyses is unknown because the sample was taken by DPW staff who are no longer with the DPW and cannot be located for consultation.